AD NUMBER
AD888407
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution: Further dissemination only as directed by Director, Defense Advanced Research Projects Agency, Arlington, VA 22203, AUG 1971, or higher DoD authority.**
AUTHORITY
USAABMDA ltr, 19 Feb 1974

WGRC 71-2251
Copy ___ of 90 Copies

CR-2-184

FINAL REPORT FOR THE OPTICAL SIGNATURES PROGRAM

Volume VI

EXOATMOSPHERIC TARGET SIGNATURES CODE (EXOSIG) USER'S MANUAL

August 1971

GENERAL RESEARCH CORPORATION
WASHINGTON OPERATIONS
1501 WILSON BLVD, SUITE 700, ARLINGTON, VA. 22209

BEST
AVAILABLE COPY

UNCLASSIFIED

This report was prepared by General Research Corporation, Washington Operations, for the U.S. Army Advanced Ballistic Missile Defense Agency under Contract DAHC60-70-C-0078. Additional funding was supplied by the Advanced Research Projects Agency of the Department of Defense under ARPA Order Number 1292, Amendment 3.

UNCLASSIFIED

14 GRC- CR-2-184 - Vol-6

9 FINAL REPORT FOR 6 THE OPTICAL SIGNATURES PROGRAM.

Volume VI.
EXOATMOSPHERIC TARGET SIGNATURES CODE (EXOSIG) USER'S MANUAL.

11 Aug~~ust~~ 1971 12 138p.

Contract Number: 15 DAHC-~~60~~-70-C-0078, ARPA Order-1292

Contractor: General Research Corporation
Washington Operations
1501 Wilson Boulevard
Arlington, Virginia 22209

Principal Investigator: 10 Thomas M. Zakrzewski
(703/524-7206)

Effective Date of Contract: 8 June 1970

Contract Expiration Date: 7 August 1971

Amount of Contract: $425,000

Title: Optical Signatures Program

STATEMENT #5 UNCLASSIFIED

This document may be further distributed by any holder only with specific prior approval of ____________________

This Research Was Supported by the
U.S. Army Advanced Ballistic Missile Defense Agency
Huntsville, Alabama 35807

attn: CRDABH-A

Mlk (405170)

FOREWORD

The material in this report was submitted to General Research Corporation by Robert Sampson, a GRC consultant, and is based upon work which he and T. W. Tuer previously performed at the University of Michigan, Institute of Science and Technology.

This report is Volume VI of the Final Report for the Optical Signatures Program and was prepared by Thomas M. Zakrzewski, Program Manager, who assumes full responsibility for the revisions of the contributions herein. The program is under the technical direction of W. O. Davies and J. L. Hayes, U.S. Army Advanced Ballistic Missile Defense Agency, Huntsville, Alabama office.

ABSTRACT

The exoatmospheric target signature code (EXOSIG), a segment of the Optical Signatures Code (OSC), is designed to calculate the optical signatures of targets (reentry vehicles, decoys, etc.) during exoatmospheric flight. EXOSIG is divided into nine distinct sections, two of which supply information to the remaining sections and not to the user of the code. These two routines (TARG and EARTH) are, therefore, presented as appendixes rather than in the main body of this volume. The remainder of the exoatmospheric code is comprised of seven primary sections, each of which is available to the user depending upon which types of targets and calculations he desires. Any number of calls may be made to any number of routines. An end-of-file test will terminate the job. The physics utilized in the development of each section's code and the input/output information necessary to or resulting from each of the calculations is different for each section and is presented. The choice of which routine (available to the user) is required by him is based upon the target configuration, its surface material properties, and whether the user desires the target's optical signature or the polarization content of its optical signature.

CONTENTS

CONTENTS (Cont.)

FIGURES

TABLES

I. EXOATMOSPHERIC TARGET SIGNATURES CODE (EXOSIG) USER'S MANUAL

The exoatmospheric target signatures code (EXOSIG) is designed to calculate the optical signatures of targets (reentry vehicles, decoys, etc.) during exoatmospheric flight. The code has the capability of calculating the heat input to a reentry vehicle during launch and its resulting optical signature during launch and midcourse. EXOSIG, as a whole, handles targets reflecting earthshine specularly, diffusely, or bidirectionally and determines both the self-emitted and reflected contributions to the optical signature. The capability for calculating the emitted contribution to the optical signature for boosters is not contained in this code because of the uncertainty in the heat input to the booster during burn. However, the reflected contribution to the optical signature for boosters (often times the most significant) can be calculated using this code.

The target radiant emission at a specific wavelength or in a wavelength interval is determined by using the temperature of the target and assuming a Lambertian radiator. The target reflected radiant intensity at a specific wavelength or in a particular wavelength interval is obtained by supplying the earth-emanating radiation at the particular wavelength or wavelength interval and using the optical material properties for the particular wavelength or wavelength interval.

The exoatmospheric code has the capability of performing seven separate calculations, therefore, the User's Manual is divided into seven distinct sections. The tasks that can be performed by using part or all of the EXOSIG routines include:

1. The calculation of the temperature and the resulting radiant emission from a reentry vehicle during launch amd midcourse for either a shrouded or unshrouded launch and with any launch trajectory (SURAD).

2. The calculations of the contribution to the optical signature of a target that is due to earth-emanating radiation that is specularly reflected from the target (SPEC1).

3. The calculations of the contribution to the optical signature of a target that is due to earth-emanating radiation that is diffusely reflected from the target (DIFUS1).

4. The calculations of the equilibrium temperature for a target of small thermal mass and the resulting directionally emitted radiant intensity. In addition, the contribution to the target optical signature due to bidirectionally reflected earth-emanated radiation is calculated (TINTF).

5. The calculation of the magnitude of the error introduced in the optical signature by using normal material properties instead of directional material properties (DIREC).

6. The calculation of the polarization content of the self-emitted radiant intensity (EP1).

7. The calculation of the polarization content of the radiant intensity from target specularly reflected earth-emanating radiation (SPOL).

Although they do not generate significant output to the user, two remaining sections (TARG and EARTH) supply information essential to the operation of the exoatmospheric code and are presented as Appendixes I and II. The relationship of TARG and EARTH to the remainder of the EXOSIG code is discussed in each of the following seven sections. In addition, the physics utilized in the development of each section's code and the INPUT/OUTPUT information necessary to or resulting from each of the calculations is different for each section and is presented. The user must decide which of the calculations he wishes to make. This decision will be based upon the target configuration, its surface material properties, and whether the user desires the target's optical signature or the polarization content of its optical signature. The user should now refer to the section of this manual concerning the type of calculation he desires.

II. REENTRY VEHICLE LAUNCH AND MIDCOURSE TEMPERATURE AND RADIANT INTENSITY CODE (SURAD)

A. INTRODUCTION

This code is designed to calculate the surface temperature of a reentry vehicle during the launch and midcourse phases of ballistic flight. This surface temperature is then used to determine the radiant emission from a reentry vehicle using HRAD (Appendix III). The HRAD code is not, at present, a part of the exoatmospheric code and must be called individually through the OSC driver program. The general procedure for obtaining the surface temperature is to determine the flow field properties during the launch phase and to use these to calculate the aerodynamic heat input to the reentry vehicle. The net heat flux is obtained by a heat balance considering aerodynamic, solar conduction to the reentry vehicle and surface radiation. During midcourse, the heat balance includes the above components except aerodynamic heating which is negligible. The heat shield temperature is determined using the net heat flux by a finite difference technique.

The procedure allows determination of the surface temperature for any body shape with a multilayered heat shield on any arbitrary ballistic trajectory. Silo blast heating and heat transfer from the booster are not included; however, any programmed heat input can be considered. Ablation and nonequilibrium effects are generally not appreciable and are not considered in this analysis.

B. DEVELOPMENT OF EQUATIONS

Any description of how launch surface temperature is calculated in itself is a description of the entire interaction of the reentry vehicle with its environment. One must begin with a body of a given shape at a specific velocity and altitude since this defines the shock conditions. A fluid particle of air must be followed through the shock and expanded to some given point in the boundary layer. Heat transfer through the boundary layer to the surface must then be calculated. Midcourse surface temperature is much easier to calculate as the corrective component of heat transfer is zero and only a heat balance is necessary.

A complete flow field description must treat regimes from free molecular through continuum flow. With the exception of a narrow transitional regime (see Fig. 1), the flow characteristics are calculable.[1,2] Since the vehicle spends a relatively short time in the transitional regime, transitional theory will not be treated. For an adequate treatment of free molecular theory, see Ref. 1 or 2.

For convenience, the discussion of continuum flow theory is presented for blunt vehicles and then for blunted slender vehicles. For this discussion, the blunt body is defined as one for which the boundary layer is fed by near-normally shocked air alone (see Fig. 2). Thus, the flow field of interest is near isentropic and surface pressure only is needed in order to describe the expansion from the stagnation region to any given point in the boundary layer. Normal shock relations for equilibrium conditions are used to determine properties behind the shock.

$$\rho_\infty V_\infty = \rho_2 V_2 \qquad \text{Continuity (II-1)}$$

$$\frac{P_2}{P_\infty} = 1 + \gamma_\infty M_\infty^2 \left[1 - \frac{V_2}{V_\infty}\right] \qquad \text{Momentum (II-2)}$$

$$\frac{h_2}{h_\infty} = 1 + \frac{(\gamma_\infty - 1)}{2} M_\infty^2 \left[1 - \left(\frac{V_2}{V_\infty}\right)^2\right] \qquad \text{Energy (II-3)}$$

$$P_2 = \rho_2 R T_2 Z_2 \qquad \text{State (II-4)}$$

where
- P is pressure
- V is velocity
- γ is the ratio of specific heats of air
- M is Mach number
- h is enthalpy
- R is the gas constant

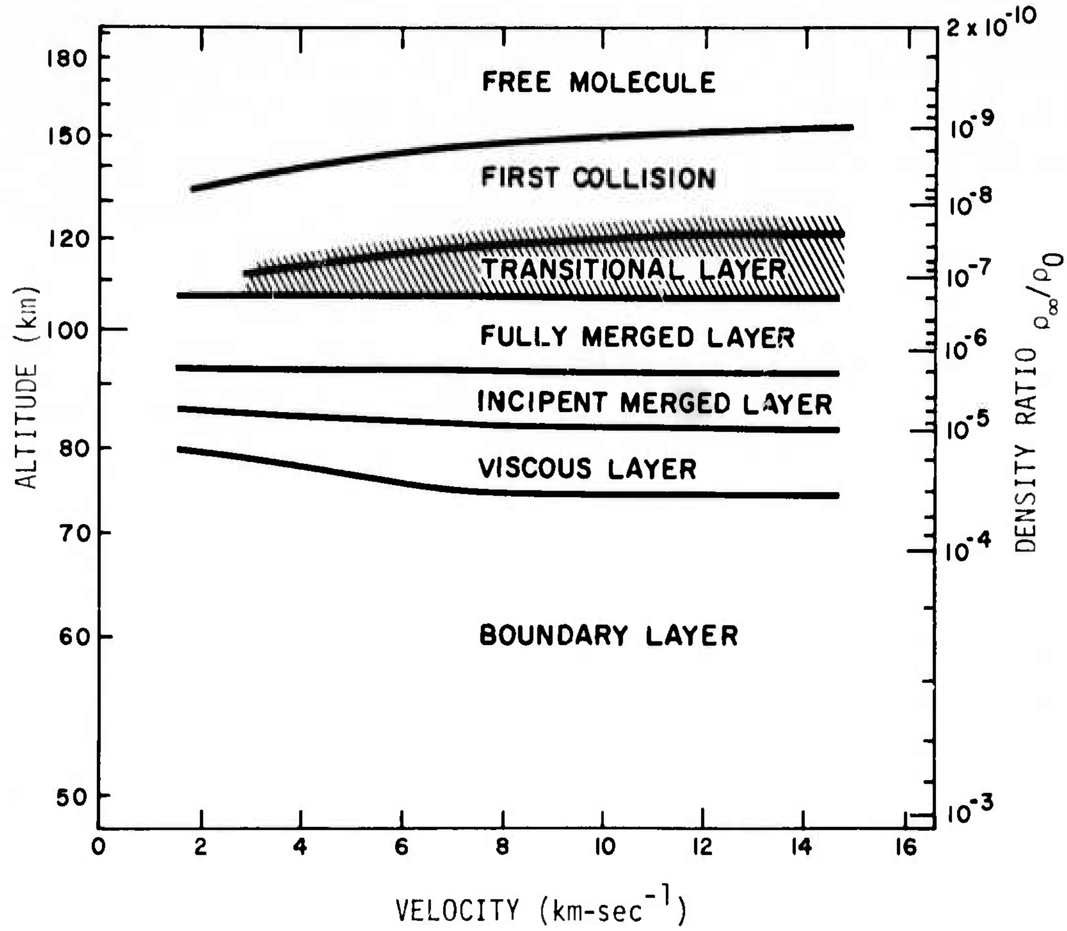


Figure 1. Rarefield Stagnation Flow Regimes for a Highly Cooled Blunt Body

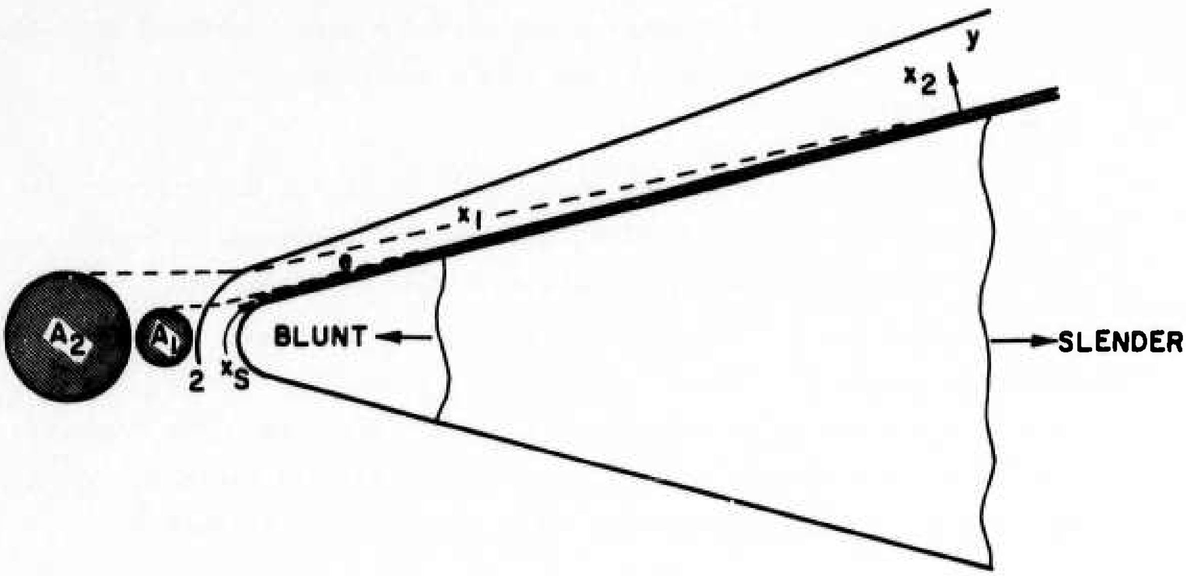


Figure 2. Flow Field Around Blunt and Slender Vehicles

T is temperature

Z is the compressibility

2 (subscript) denotes properties immediately behind the shock

∞ (subscript) denotes ambient properties

An iterative procedure[3] is employed to determine these properties. Equilibrium normal shock conditions are expanded isentropically to a surface pressure determined from empirical data or calculated using modified Newtonian theory. Although modified Newtonian theory breaks down at the sphere-cone juncture for small cone angles, reasonable accuracy is obtained if one looks at distances far from this juncture. The cone-cone expansion (if the vehicle design is such) is similarly treated. State properties for equilibrium air are those published by Feldman.[4]

The blunted-slender body is one for which the boundary layer is is fed by obliquely shocked, as well as normally shocked air. The region of transition from normally shocked air to obliquely shocked air is not considered, only points before and after transition. Thus, flow properties at the external side of the boundary layer are determined before oblique shock influence and after obliquely shocked air dominates boundary layer flow.

The location of this transition region is determined by a mass-flow-rate balance (see Fig. 2).

$$x_1: \quad \rho_\infty V_\infty A_1 = 2\pi \rho_{e_1} V_{e_1} (\delta - \delta^*)_1 r(x_1) \tag{II-5}$$

$$x_2: \quad \rho_\infty V_\infty A_2 = 2\pi \rho_{e_2} V_{e_2} (\delta - \delta^*)_2 r(x_2) \tag{II-6}$$

where δ is the boundary-layer thickness

δ^* is the displacement thickness: $\delta^* = \int_0^\delta \left(1 - \frac{\rho V}{\rho_e V_e}\right) dy$

ρ_e is the local density at the external side of the boundary layer

V_e is the local velocity at the external side of the boundary layer

ρ_∞ is the free-stream density

V_∞ is the free-stream velocity

r is the radial distance from the longitudinal axis of the reentry vehicle

Chapman[5] gives δ and δ^* as functions of surface distance x for laminar cones at a variety of conditions. A_1 and A_2 are the areas defined by 10° deviations from the normal and the asymptotic oblique shock, respectively. Shock shapes for spherical-nosed bodies are obtained from existing experimental and theoretical results.[6] Thus, the limits of this transition region (x_1 and x_2) may be determined from the above equations. The region of influence of normally shocked air ($x < x_2$) agrees well with that given by Chernyi.[7]

Since we know the limits of the transition region, external flow properties for the regions $x < x_1$ and $x > x_2$ may be determined by expanding isentropically to a "Modified Newtonian" or empirical pressure from normal and oblique shock properties, respectively.

The calculation of the surface temperature of a reentry vehicle requires determination of the net heat-transfer rate to the surface and the rate of conduction of the heat within the heat shield. The net heat-transfer rate to the surface is comprised of the radiative and convective or aerodynamic contributions. The calculations of the surface radiation then utilizes the calculated surface temperature assuming the surface to be a Lambertian radiator (Appendix III).

Semi-empirical heat-transfer relationships are available for all flow regimes with the exception of the narrow transitional regime discussed in inviscid flow-field theory. However, as opposed to flow-field theory, heat-transfer theory may be used in its full form to perform inexpensive calculations on simple configurations. Therefore, approximations to the full theory will not be discussed.

Neglecting the thermal motion of the molecules, the convective heat-transfer rate in the free-molecular flow regime can be expressed as

$$q = q_{conv} = \frac{\alpha \rho_\infty V_\infty^3 \sin \theta}{2} \tag{II-7}$$

where α is the accommodation coefficient $(0 < \alpha < 1)$

ρ is the density

V is the velocity

θ is the angle of attack

There is great uncertainty about the numerical value of α. No laboratory tests of accommodation coefficients for typical reentry vehicle materials or with particle energies appropriate to reentry velocities have been published, but the problem is discussed by Patterson,[8] and Wachman.[9] The uncertainty in α is not critical because the body is in appreciable free-molecular heating for only a short period of time.

The heat-transfer rate in the equilibrium flow region of the continuum regime is needed to determine the heat transfer rate for the laminar stagnation point, and laminar and turbulent flow conditions on other portions of the reentry vehicle. The heat transfer to the stagnation point as given by Fay and Riddell,[10] is

$$q_s = \frac{0.763}{Pr^{0.6}}(\rho\mu)_w^{0.1}(\rho\mu)_e^{0.4}\left[1 + (Le^{0.52} - 1)\frac{h_{D_s}}{h_s}\right](h_s - h_w)\left\{\frac{1}{R_N}\left[\frac{2(P_s - P_\infty)}{\rho_s}\right]^{1/2}\right\}^{1/2} \tag{II-8}$$

where μ is the coefficient of viscosity (lbf-sec-ft^{2})

Pr is the Prandtl number

h is the enthalpy (BTU-lbm^{-1})

Le is the Lewis number

h_D is the average atomic-dissociation energy times atom-mass fraction in external flow

R_N is the noise radius (ft) (radius of curvature at the stagnation point)

P is pressure (lbf-ft^{-2})

s (subscript) is the stagnation point

w (subscript) is the wall

e (subscript) is the external side of the boundary layer

The laminar heat-transfer rate of station x on a blunt body, as given by Avco-Everett,[11] is

$$q_x = \frac{q_s}{\sqrt{2P_{e_s} A_{T_s} \left(\frac{dV_e}{ds}\right)_s}} \sqrt{\frac{\mu_0}{RT_0}} \frac{r V_e P_e A_T}{\sqrt{2\xi}} \left(1 + \frac{0.096\sqrt{\beta}}{1.068}\right) \left(\frac{h_\lambda - h_w}{h_s - h_{w_s}}\right) \tag{II-9}$$

where $A_T = (T_w/T_0)^{1/2}(T_0 + 202)/(T_w + 202)$

$$\xi = \mu_0/RT_0 \int_0^x A_T P_e V_e r^2 \, dx$$

$$\beta = \left(2\xi/V_e\right)\left(dV_e/d\xi\right) = \left(2\xi/A_T P_e V_e^2 r^2\right)\left(dV_e/dx\right)$$

$$h_\lambda = h_s[\lambda + h_e/h_s(1 - \lambda)] = h_e + \frac{V_e^2 \lambda}{2}$$

x = wetted length, or distance transversed by following the curved path of the body surface downstream from the stagnation point to the desired station

π = recovery factor

r = radial distance from the longitudinal axis of the vehicle

Although derived for blunt bodies, (Eq. II-9), when applied to a simple cone, gives values of q_x which agree with values obtained from an empirical relation derived by AVCO-RAD.[12]

The turbulent heat-transfer rate at station x, also according to AVCO-RAD,[13] is

$$q_T = \frac{26.6}{Pr^{2/3}}\left(\frac{\rho^*}{\rho_0}\right)^{0.8}\left(\frac{\mu^*}{\mu_0}\right)^{0.2}\left(\frac{h_s}{RT_0}\right)^{1.4}\left[1 - \frac{h_e}{h_s}\right]^{0.4}\frac{x^{-0.2}(Re_x)^{0.2}}{(\log_{10}Re_x)^{2.58}}\,\frac{h_\pi - h_w}{h_s} \qquad \text{(II-10)}$$

in which Re is the Reynolds number and * indicates a quantity evaluated at P_e and h*, where

$$\frac{h^*}{h_e} = 1 + 0.5\left(\frac{h_w}{h_e} - 1\right) + 0.22\pi\left(\frac{h_s}{h_e} - 1\right)$$

As an indication of the similarity of heat-transfer relationships used by investigators, compare the following relation for turbulent-heat-transfer rate as used by GE,[14] with that of AVCO-RAD above:

$$q_T = \frac{0.0296\rho_e V_e(\mu_e)^{0.25}\left(\frac{\mu^*}{\mu_e}\right)^{0.2}\left(\frac{\rho^*}{\rho_e}\right)^{0.8}(r)^{0.25}(h_\pi - h_w)}{Pr^{2/3}\left(\int_0^x \rho_e V_e \mu_e^{0.25} r^{1.25}\, dx\right)^{0.2}} \qquad \text{(II-11)}$$

For a conical body (constant flow properties on cone), this reduces to

$$q_T = \frac{3.804}{Pr^{2/3}}\left(\frac{\rho*}{\rho_0}\right)^{0.8}\left(\frac{\mu*}{\mu_0}\right)^{0.2}\left(\frac{V_e^2}{RT_0}\right)^{0.4}\left(\frac{h_r - h_w}{RT_0}\right)x^{-0.2}$$

(II-12)

Further, note that for $10^4 < Re_x < 10^8$, the "Re_x term" in Eq. II-10 varies from 0.156 to 0.189. Thus, Eq. II-10 can be approximated by

$$q_T \simeq \frac{3.33}{Pr^{2/3}}\left(\frac{\rho*}{\rho_0}\right)^{0.8}\left(\frac{\mu*}{\mu_0}\right)^{0.2}\left(\frac{V_e^2}{RT_0}\right)^{0.4}\left(\frac{h_r - h_w}{RT_0}\right)x^{-0.2}$$

(II-13)

where $(h_s - h_e)$ has been equated to $V_e^2/2$. The AVCO and GE equations now differ by a constant factor of only 1.14. The above theory adequately handles both blunt and slender vehicles.

Although the AVCO equations were developed for hypersonic flow, they give accurate results at Mach numbers below five. At Mach three, the AVCO equations agree within ten percent with results obtained using theorv developed by E. R. Van Driest[15] for low Mach number flight.[16]

The previous theoretical treatments have assumed equilibrium chemistry. Nonequilibrium effects are not a significant factor for liquid fuel booster launches and are significant for solid-fuel booster launches only at altitudes after peak heating. Therefore, nonequilibrium effects are neglected in this analysis.

The radiative heat transfer consists of absorption from high-temperature shocked air and thermal (surface) emission. Other components, (solar and earth emanating) are negligible during launch, but are significant during midcourse.

In the stagnation region, the maximum radiative heat-transfer from high-temperature-shocked air encountered by current reentry vehicles is approximately one order of magnitude less than the convective heat-transfer. At positions aft of the stagnation region, the ratio of radiative to convective heat transfer is much lower and the radiative heat-transfer may be neglected. Therefore, the radiative heat-transfer is accounted for only at the stagnation point. The equation used is an approximate relationship given by Detra and Hidalgo:[17]

$$\frac{q_g}{R_N} = K_1\left(\frac{V_\infty}{K_2}\right)^{8.5}\left(\frac{\rho_\infty}{\rho_0}\right)^{1.6} \tag{II-14}$$

where $K_1 = 10^2$ in the English system and 3.16×10^{-2} in the CGS system; and $K_2 = 10^4$ in the English system and 3.05×10^5 in the CGS system. A similar equation is given by Warzecha,[18]

$$q_g = C\rho_\infty^{3/2} M_\infty^8$$

where C is a constant for a given configuration and M is the Mach number.

Thermal emission is extremely important in maintaining a heat balance. Indeed, for high-surface temperature, the thermal emission q_e is of a comparable magnitude to the aerodynamic heating:

$$q_e = C_1\int_0^\infty \varepsilon(\lambda)\lambda^{-5}\left(e^{C_2/\lambda T_w} - 1\right)^{-1} d\lambda \tag{II-15}$$

where $\varepsilon(\lambda)$ is the spectral emissivity of the surface

T_w is the wall temperature

λ is the wavelength

$$C_1 = 3.7413 \times 10^4 \text{ W-cm}^{-2}\text{-}\mu\text{m}^4$$

$$C_2 = 1.43 \times 10^4 \ \mu\text{m} - \text{K}$$

If we combine Eqs. II-14 and II-15, the net heat-transfer to the vehicle surface during launch is written

$$q_{net} = q_{aero} + K_1 R_N \left(\frac{V_\infty}{K_2}\right)^{8.5} \left(\frac{\rho_\infty}{\rho_0}\right)^{1.6}$$

$$- C_1 \int_0^\infty \varepsilon(\lambda)\lambda^{-5}\left(e^{C_2/\lambda T_w} - 1\right)^{-1} d\lambda \qquad \text{(II-16)}$$

and q_{aero} is given by Eqs. II-7-10 depending upon the flow condition.

During midcourse the equation for heat transfer is

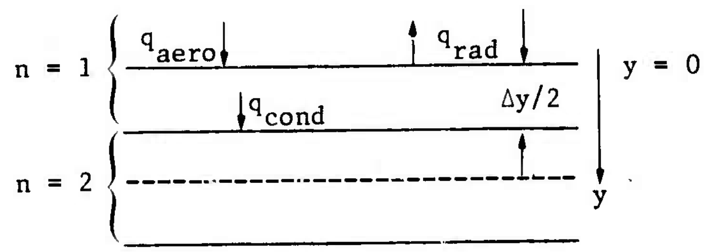
$$q_{net} = q_{earth\ emanating} + q_{solar} - C_1 \int_0^\infty \varepsilon(\lambda)\lambda^{-5}\left(e^{C_2/\lambda T_w} - 1\right)^{-1} d\lambda \qquad \text{(II-17)}$$

q_{solar} is the solar radiation constant or zero. However, $q_{earth\ emanating}$ varies with season, time of day, and cloud condition. Since the reentry vehicle has a large mass and the flight time is of relative short duration, the effects of these fluctuations is negligible and a mean value is assumed.

Because of the nonlinear character of the net heat-transfer boundary condition, surface-temperature determination requires a computer solution of Fourier's conduction equation. A standard finite difference method of handling this problem is summarized in the following paragraph.

Since a steep temperature gradient exists, the surface temperature must be calculated by considering small intervals normal to the surface. For an insulated inner surface, the temperature at all intervals at time $t + \Delta t$ may then be expressed as functions of the heat input and the interval temperatures at time t.

The first interval (outer surface)



$$q_{net} = q_{aero} - q_{rad}$$

$$q_{net} - q_{cond} = q_{absorbed}$$

Transposing, and substituting for $q_{absorbed}$ and q_{cond}:

$$T_{1,t+\Delta t} = \frac{q_{net}\left(\frac{\Delta y}{k}\right) + T_{2,t} + \left(\frac{A}{2} - 1\right) T_{1,t}}{A/2}$$

where

$$A = C_p \, \rho (\Delta y)^2 / k\Delta t$$

K is the thermal conductivity of the material

C_p is the specific heat of the material

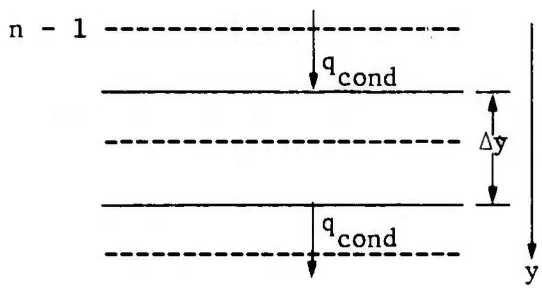
ρ is the density of the material

The above equation expresses the unknown surface temperature at a future time $(t + \Delta t)$ as a function of the variables

$$T_{1,t+\Delta t} = f(q_{net}, T_{1,t}, T_{2,t})$$

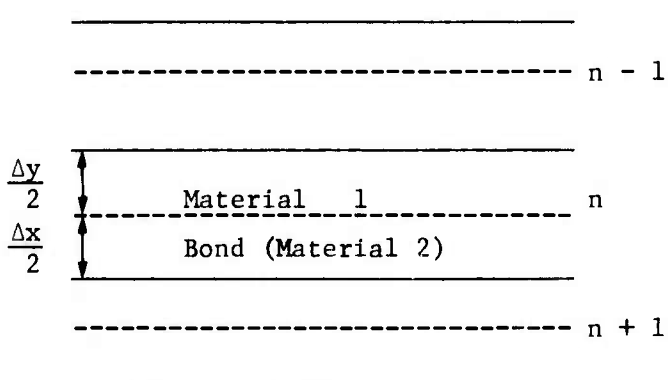
The heat balance must be formulated in subsequent intervals to determine $T_{n,t+\Delta t}$.

The general interval:



$$T_{n,t+\Delta t} = \frac{\left[T_{n-1} + T_{n+1} + (A - 2)T_n\right]_t}{A} \qquad \text{(II-18)}$$

The temperature of the interval of a material-bond interface is expressed as follows:



$$T_{n,t+\Delta t} = T_{n,t} + \left[k_2\left(\frac{T_{n+1,t} - T_{n,t}}{\Delta x}\right) - k_1\left(\frac{T_{n,t} - T_{n-1,t}}{\Delta y}\right)\right]$$

$$\frac{2\Delta t}{\rho_1 C_{p_1} \Delta\lambda + \rho_2 C_{p_2} \Delta x} \qquad \text{(II-19)}$$

The temperature of the last interval of the structure can be expressed as

$$T_{n,t+\Delta t} = \frac{\left[T_{n-1} + \left(\frac{A}{2} - 1\right) T_n\right]_t}{A/2} \qquad \text{(II-20)}$$

where A is calculated using the structure properties.

Temperatures at all intervals at time $t + \Delta t$ have been expressed as functions of the net rate of heat transfer and interval temperatures at time t. Since the net heat transfer rate is a function of surface temperature, an iterative procedure is necessary to determine surface temperature.

C. INPUT/OUTPUT SPECIFICATIONS

These equations are combined in the code SURAD for calculating reentry vehicle launch and midcourse surface temperature. Prior to using the code, the reentry vehicle must be divided into isothermal areas. The temperature for a central point (station) in each area will be calculated. The heat shield at each station is divided into sublayers with the thickness of each sublayer determined by the requirement that A (see Eq. II-17) be greater than 2. This is necessary when using a finite difference technique for temperature calculation.

Output generated by SURAD includes a time versus temperature array of each layer of heat shield material for launch and/or midcourse. In addition, the surface temperature from the code can be put into HRAD (Appendix III) to determine the radiant emission from a reentry vehicle.

The input data necessary for using this code is tabulated below and must be read in the English system of units. As many data sets as the user requires may be input with only one call to SURAD. Since the SURAD code runs independently of all remaining routines in the EXCSIG package, the first data card provided for input to SURAD must contain the letters SUR in the first three columns to designate that the operator desires to make a reentry vehicle surface temperature calculation.

Since arrays LD through Z defined below remain constant for a majority of cases, input data for these are stored on a permanent file (See Appendix IV). If the user wishes to use the standard input to arrays LD through Z, he must set the "ITAPE" input variables in the second data card to "2". If, on the other hand, the user wishes to use only a part or none of the standard input, he must set the "ITAPE" input variables to "5" for each of the arrays LD through Z which is to use nonstandard input. A definition of each of the standard arrays is given below.

Input Data For SURAD

LD(1)...LD(41) are forty-one numbers used to determine the density of the atmosphere as a function of altitude from 0 to 122 km.

END3(1)...END3(44), END4(1)...END4(44) are eighty-eight numbers which represent end points of the Mollier diagram[4] of pressure versus entropy. These end points are necessary to indicate when to use the Mollier diagram for determining properties.

LM(1)...LM(9), ZPP(1)...ZPP(9), TM(1)...TM(9) are three fields, each of nine numbers, are used to determine the temperature of the atmosphere as a function of altitude from 0 to 100 km.

TB is the lower boundary temperature of the Mollier diagram.

R is the universal gas constant.

PO is reference pressure.

MINT42 and EPSI42 are the increment and minimum value of pressure used in the tabulation of the Mollier diagram.

C1 and C2 are the constants of the first degree polynomial for enthalpy as a function of temperature.

END1(1)...END1(36), END2(1)...END2(36) are seventy-two numbers which represent end points of the Mollier diagram[4] of pressure versus entropy. These end points are necessary to indicate when to use the Mollier diagram for determining properties.

RHOO is reference density.

MUO is reference viscosity.

RETRAN is the theoretical critical Reynolds Numbers.

HB is the base enthalpy of the Mollier diagram.

LE is Lewis Number.

PR is Prandtl Number.

TO is reference temperature.

IKL is the number of iterations allowed on the hot wall heat transfer loop in HTEMLP. When this condition is exceeded, the iterative loop is completed and the next station is examined.

GL is the number of iterations allowed on the surface temperature loop in HTEMLP. When this condition is exceeded, adequate convergence has not been obtained and the program is terminated.

ERROT is the maximum allowable error in the surface temperature iterative loop in HTEMLP.

ERORT is the maximum allowable error in the hot wall heat transfer iterative loop in HTEMLP.

TEMPER,H,Z are 36 × 44 arrays that contain the temperature, entalopy, and compressibility factors for the Mollier diagram. The three tables of prints are discrete points on a Mollier diagram of pressure versus entropy.

[The remaining data will vary for each reentry vehicle and launch trajectory and must be supplied by the user.]

IENO is an end-of-data test parameter. If = 0, data follows. If = 9999, no more data is to be read in.

ERRORU is the maximum error allowable in the velocity ratio in HALTLP in percent.

ACCOM is the accommodation coefficient.

DT is the time increment in seconds before vehicle left atmosphere.

FT is the initial flight time in seconds.

ENDFM is the altitude of transition from continuum to free molecular flow in kilofeet.

ENDCON is the altitude of the end of launch heating and the beginning of midcourse flight in kilofeet.

DE is an array of cone angles for oblique shock in degrees.

KL is the number of cone angles on the body.

TIC is the subscript of the fir altitude that launch heating is to be calculated for.

IL Set = 2 If both sunlit and earth heating sections of midccurse calculations are desired.

Set = 1 If only sunlit section is desired.

Set = 0 If only earth heating section is desired.

LAUNCH is 1 if launch heating is to be calculated and 0 is only midcourse heating is to be calculated. (1 = unshrouded, 0 = unshrouded)

IOPRINT is the printing increment for all cases after vehicle has left atmosphere.

ICREMTIM is the printing increment for time interval before vehicle has left atmosphere.

TL is the subscript of the last altitude and velocity to be input.

TIR is the subscript of the first velocity altitude input.

KS(TIC)...KS(TL) is a table of shock angle as a function of velocity for a specific cone angle in degrees.

ALT(TIR)...ALT(TL), VAM(TIR)...VAM(TL) is the launch altitude and velocity history respectively in kilofeet and kilofeet/second.

NL is the number of stations on the reentry vehicle.

NOBLI is the front station feed by obliquely shocked air.

RETURB is the front station at which turbulent flow occurs.

NSPHER is the number of stations on the sphere.

NICONE is the front station for which empirical pressure measurements are available.

RN is the nose radius of the reentry vehicles in feet.

TRANSA is the empirical altitude at which transition to laminar flow first occurs in kilofeet.

TRNALT is the empirical altitude at which transition to laminar flow occurs if the entire reentry vehicle appears to become laminar instantaneously in kilofeet.

VAMOBL is the velocity at which the flow field at the last station on the reentry vehicle begins to be fed by obliquely shocked air in kilofeet/second.

X is the surface distance from each station to the stagnation point in feet.

X1 is the surface distance from the foremost point in the station to the stagnation point in feet.

DELTA is the surface angle at the station measured from the axis of symmetry in radians.

RAD is the radius of the station measured from the axis of symmetry in feet.

RI is the radius of the foremost point in the station measured from the axis of symmetry in feet.

TINI is the initial temperature of each station of the reentry vehicle in °R.

TSTL2 is the surface temperature at (TIC-2) in °R.

TITL2 is the second layer temperature at (TIC-2) in °R.

FRAC is the "gain" in the wall temperature. Initially it is equal to 1.0.

QH1 is the hot wall transfer at time (TIC-1) in BTU/ft^2-sec.

NTI is the time of the first calculation in midcourse in seconds.

NTL is the time of the last calculation in midcourse in seconds.

PHI is the absorptivity of the outer heat shield material in the visible region.

NDELT is the time increment during midcourse in seconds.

DELSTR is the thickness of the structure in inches.

RHOSTR is the density of the structure material in lbm/ft^3.

CPSTRU is the heat capacity of the structure material in BTU/lbm-°R.

CONSTR is the thermal conductivity of the structure material in BTU/ft-°R-hr.

DELY2 is the thickness of the bond between the first and second layers of heat shield material in inches.

RHOM2 is the density of the bond material between the first and second layers of heat shield material in lbm/ft^3.

NTF is the last time in the continuum regime before entering the free molecular regime. It is the time of the last altitude before ENDFM in seconds.

CP2 is the heat capacity of the bond material between the first and second layers of heat shield material in BTU/lbm-°R.

CON2 is the thermal conductivity of the bond material between the first and second layers of heat shield material in BTU/ft-°R-hr.

DELY3 is the thickness of each sublayer of the second layer of heat shield material in inches.

RHOM3 is the density of the second layer of heat shield material in lbm/ft^3.

CP3 is the heat capacity of the second layer of heat shield material in BTU/lbm-°R.

CON3 is the thermal conductivity of the second layer of heat shield material in BTU/ft-°R-hr.

DELY4 is the thickness of the bond between the second and third layers of heat shield materials in inches.

RHOM4 is the density of the bond material between the second and third layers of heat shield material in lbm/ft^3.

CP4 is the heat capacity of the bond material between the second and third layers of heat shield material in BTU/lbm-°R.

CON4 is the thermal conductivity of the bond material between the second and third layers of heat shield material in BTU/ft-°R-hr.

DELY5 is the thickness of each sublayer of the third layer of heat shield material in inches.

RHOM5 is the density of the third layer of heat shield material in lbm/ft^3.

CP5 is the heat capacity of the third layer of heat shield material in BTU/lbm-°R.

CON5 is the thermal conductivity of the third layer of heat shield material in BTU/ft-°R-hr.

DELY6 is the thickness of the bond between the third layer of heat shield material and the structure in inches.

RHOM6 is the density of the bond between the third layer of heat shield material and the structure in lbm/ft^3.

CP6 is the heat capacity of the bond material between the third layer of heat shield material and the structure in BTU/lbm-°R.

CON6 is the thermal conductivity of the bond material between the third layer of heat shield material and the structure in BTU/ft-°R-hr.

ENDFL(1) is the number of sublayers of the first heat shield material.

ENDTL is the number of the last sublayer of the second heat shield material.

ENDFIF is the number of the last sublayer of the third heat shield material.

NLL is the total number of layers of heat shield material.

DELY is the thickness of each sublayer of the outer layer of heat shield material in inches.

RHOMAT is the density of the outer layer of heat shield material in lbm/ft^3.

CP is the heat capacity of the outer layer of heat shield material in BTU/lbm-°R.

CON is the thermal conductivity of the outer layer of heat shield material in BTU/ft-°R-hr.

EMIT is the emissivity of the outer layer of heat shield material.

TABLA is the ablation temperature of the outer layer of heat shield material in °R.

PRH and PRO are the coefficients of the linear equation used to calculate pressure at stations NICONE to NL. PRO and PRH are determined from empirical data if it is available.

III. CODE FOR EARTHSHINE SPECULARLY REFLECTED FROM TARGET (SPEC1)

A. INTRODUCTION

This computer code is designed to calculate the specularly reflected earthshine component of the optical radiation signature of an exoatmospheric target. The general procedure is to subdivide the target into elemental areas and determine the contribution from each element, if the earthshine reflects in the direction of the viewer. Input tables calculated by TARG (Appendix I) are required, so the assumptions implicit in that code are also pertinent here. In addition, the target is assumed to be small with respect to its distance to the detector and to the earth's surface.

B. DEVELOPMENT OF EQUATIONS

The radiant intensity of an incremental area dA of the target specularly reflecting radiance $L_\lambda(\phi)$ from an earth element, toward a detector (Fig. 3) can be written as

$$dI = \rho^s L_\lambda(\phi) dA \cos\theta \tag{III-1}$$

where ρ^s is the specular reflectivity of the material.

To find the total radiant intensity due to reflected earthshine, this expression is integrated over all of the target that is visible to the detector and from which specular reflection from the earth is possible. The angle θ indicated in Fig. 3 is determined as follows:

$$\vec{R} = \vec{V} - \vec{T} \tag{III-2}$$

$$\cos\theta = \vec{R} \cdot \hat{n}/R1 \tag{III-3}$$

where $\hat{n}$ is the unit normal to the target element, R1 is the magnitude of $\vec{R}$ and is obtained from

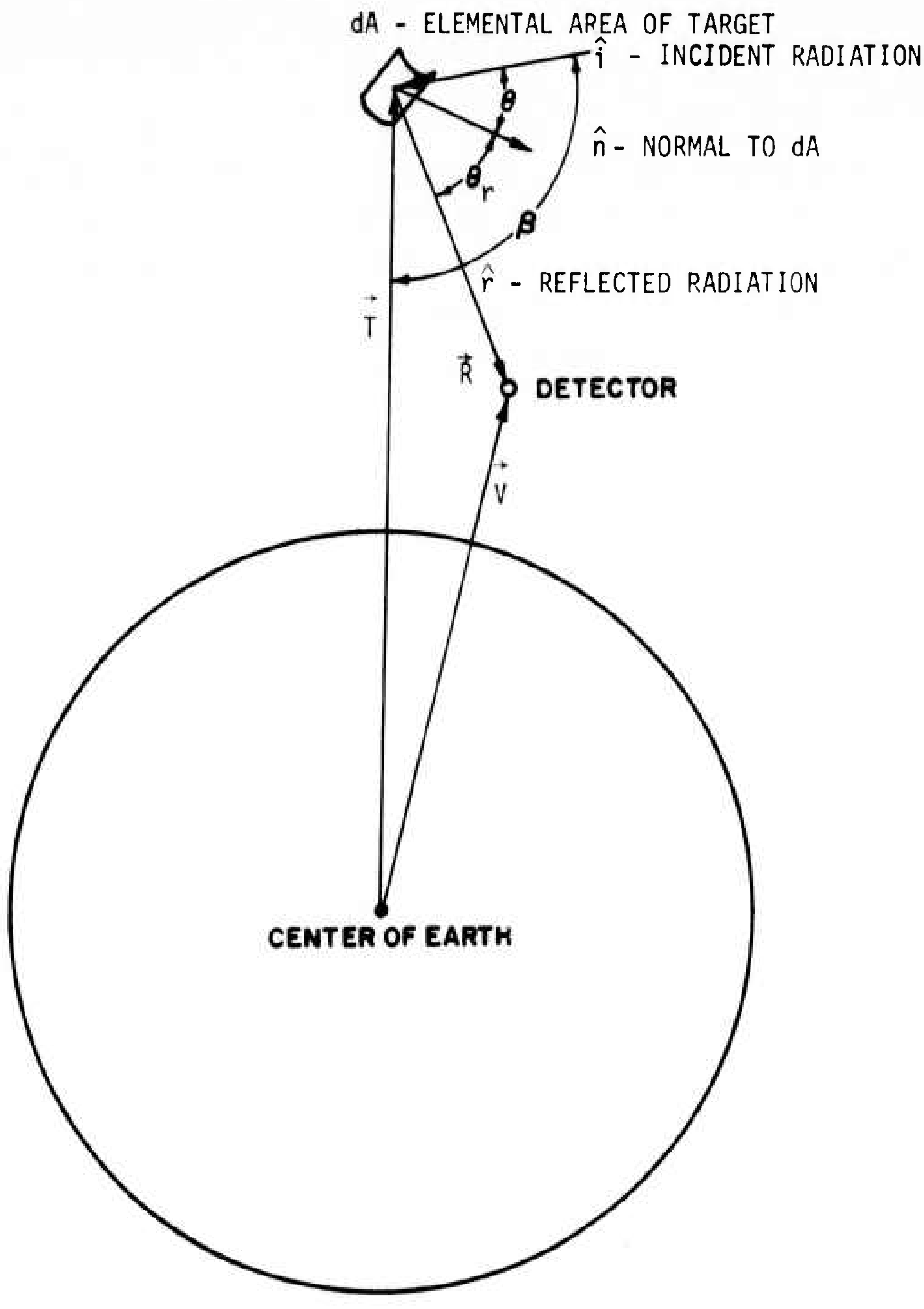


Figure 3. Specular Reflection Geometry

$$R1 = (R_x^2 + R_y^2 + R_z^2)^{1/2} \qquad \text{(III-4)}$$

where R_x, R_y, and R_z are the components of $\vec{R}$ in an earth fixed coordinate system.

If θ is greater than 90°, there is no radiation to the viewer. When θ is less than 90°, one must determine the vector $\hat{i}$ for each element and ensure that it intersects the earth. Three independent equations are required in order to determine the three components of $\hat{i}$. Two independent equations are determined from the relationship (Fig. 3)

$$\hat{n} \times \hat{r} = \hat{i} \times \hat{n} \qquad \text{(III-5)}$$

and the third from the relationship

$$\hat{r} \cdot \hat{n} = \hat{n} \cdot \hat{i} \qquad \text{(III-6)}$$

To ensure that the vector $\hat{i}$ intersects the earth, the angle β (Fig. 3) is calculated from the relationship

$$\vec{T} \cdot \hat{i} = \cos\beta \qquad \text{(III-7)}$$

If $\beta < \phi$, where ϕ = arc sin (earth radius/earth radius and target altitude), then the vector $\hat{i}$ intersects the earth and the element contributes to the specularly reflected radiant intensity of the target.

C. INPUT/OUTPUT SPECIFICATIONS

Before SPEC1 can be called, TARG must be requested by the user (see Appendix I). As many calls as required may then be made to SPEC1 without recalling the TARG code.

Table 1 defines the input data necessary for using the code. The first data card provided for input to SPEC1 must contain the letters SPE in the first three columns to indicate the operator desires to make a specular reflected signature calculation.

The output generated by SPEC1 includes the following:

1. Projected area (sq mi)
2. View factor normalized to frontal projected area
3. View factor for radiation calculation normalized to projected area
4. Nadir angle (degrees)
5. Aspect angle (degrees)
6. Radiant intensity (W/sr)

TABLE 1

INPUT DATA FOR SPEC1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
VALT	Detector altitude normalized to radius of earth	dimen-sionless	≥ 1	1.01	1.01
VLAT	Detector latitude	degrees	-90. to +90.	0.	0.
VLON	Detector longitude	degrees	0. to 360.	0.	0.
WRITE	Control parameter. If = 0, writes no intermediate results. If = 1, writes intermediate results for debug purposes.	dimen-sionless	1. or 0.	0.	0.
TALT	Target altitude normalized to radius of earth	dimen-sionless	$\geq 1.$	1.125	1.125
TLON	Target longitude	degrees	0. to 360.	0.	0.
TLAT	Target latitude	degrees	-90. to +90.	90.	90.

TABLE 1 (Cont.)

INPUT DATA FOR SPEC1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
D	Nadir angle	degrees	0. to 180.	0.	0.
ND	Control parameter for number of nadir angles. If ≤ 0 input viewer lat., long. & alt. If > 1, calculates output for ND nadir angles	dimen-sionless	N.A.	0	0
NAZ	Control parameter for number of azimuth angles to be calculated. If > 1, calculates output for NAZ azimuth angles	dimen-sionless	N.A.	0	0
AZ	Azimuth angle	degrees	0. to 180.	0.	0.
DI	If more than one nadir value to be calculated, this is the first	degrees	0. to 180.	0.	0.
DF	If more than one nadir angle to be calculated, this is the last	degrees	0. to 180.	180.	180.
AZI	If more than one azimuth angle to be calculated, this is the first	degrees	0. to 180.	0.	0.

TABLE 1 (Cont.)

INPUT DATA FOR SPECT

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
AZF	If more than one azimuth angle to be calculated, this is the last	degrees	0. to 180.	180.	180.
APF	Front projected area of the target	cm^2	N.A.	100.	100.
ESN	Earthshine radiance	$W/sr\text{-}m^2$	N.A.	1.	N.A.
RHO	Reflectance of target	1	N.A.	1.	N.A.

IV. CODE FOR EARTHSHINE DIFFUSELY REFLECTED FROM TARGET (DIFUS1)

A. INTRODUCTION

This computer code is designed to calculate the diffusely reflected earthshine component of the optical radiation signature of an exoatmospheric target. The general procedure is to subdivide the target and the portion of the earth illuminating it into elemental areas. A double numerical integration is then performed considering the elements behave as flat plates. Input tables calculated by other codes EARTH (Appendix II and TARG (Appendix I) are required, so the assumptions implicit in them are also pertinent here. In addition the target is assumed to be small with respect to its distance to the detector and to the earth's surface.

B. DEVELOPMENT OF EQUATIONS

The radiant intensity of an incremental area dA of the target diffusely reflecting incident irradiance dE from an earth element and toward a detector (see Fig. 4) can be written as:

$$dI = \frac{\rho dE dA}{\pi} \cos\theta \cos\phi \qquad \text{(IV-1)}$$

where ρ is the reflectance of the material. To find the total radiant intensity (due to reflected earthshine) this expression is integrated over all the earth which is illuminating the target and over all the target which is visible to the detector. Using vector algebra the cosine terms are simply

$$\cos\theta = \hat{n} \cdot \hat{i} \qquad \text{(IV-2)}$$

$$\cos\phi = \hat{n} \quad \hat{r} \qquad \text{(IV-3)}$$

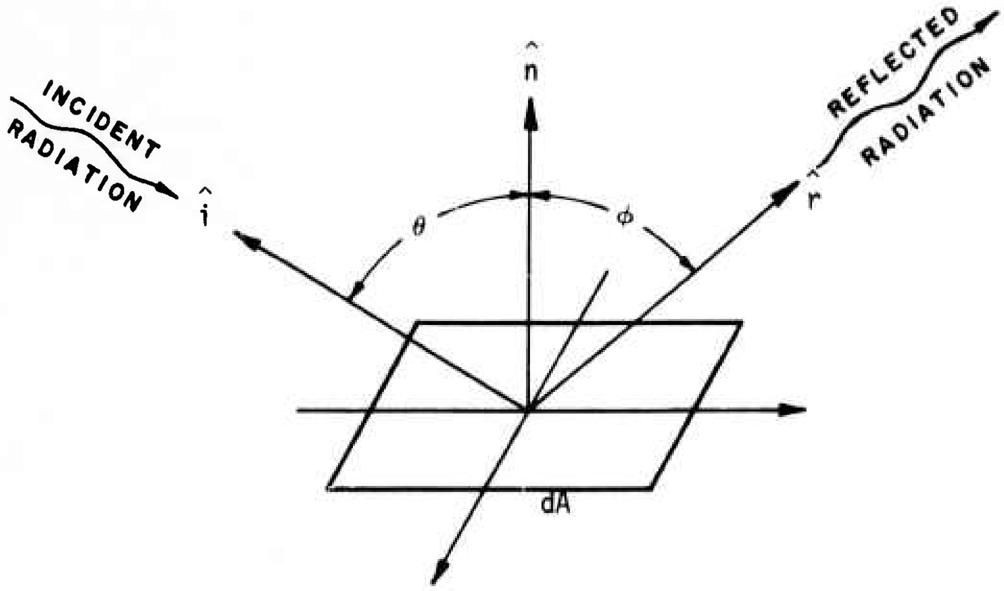


Figure 4. Reflection Geometry

where $\hat{n}$ is the unit normal vector of the element, $(\hat{n} = \vec{A}/|\vec{A}|)$, $\hat{i}$ is a unit vector toward the source of the incident radiation (e.g., an earth element), and $\hat{r}$ is a unit vector toward the detector.

Given the latitude ψ, longitude λ, and altitude β (normalized to earth radius) of the target (subscript t) and the detector, (subscript d) their position vectors $\vec{R}_t$ and $\vec{R}_d$ may be written in an earth-fixed coordinate system as:

$$\vec{R}_t = \beta_t(\hat{e}_x \cos\psi_t \cos\lambda_t + \hat{e}_y \cos\psi_t \sin\lambda_t + \hat{e}_z \sin\psi_t) \quad \text{(IV-4)}$$

$$\vec{R}_d = \beta_d(\hat{e}_x \cos\psi_d \cos\lambda_d + \hat{e}_y \cos\psi_d \sin\lambda_d + \hat{e}_z \sin\psi_d) \quad \text{(IV-5)}$$

where $\hat{e}_x$, $\hat{e}_y$, and $\hat{e}_z$ are shown in Fig. 5. Using these position vectors, the vector $\vec{r}$ is simply:

$$\vec{r} = \vec{R}_t - \vec{R}_d \quad \text{(IV-6)}$$

and

$$\hat{r} = \vec{r}/|\vec{r}| \quad \text{(IV-7)}$$

Alternatively, if the nadir angle δ and the azimuth angle χ to the viewer relative to the target is specified (see Fig. 6) we can write simply:

$$\hat{r} = \hat{e}_x \sin\delta \cos\chi + \hat{e}_y \sin\delta \sin\chi - \hat{e}_z \cos\delta \quad \text{(IV-8)}$$

where the target is located on the z axis.

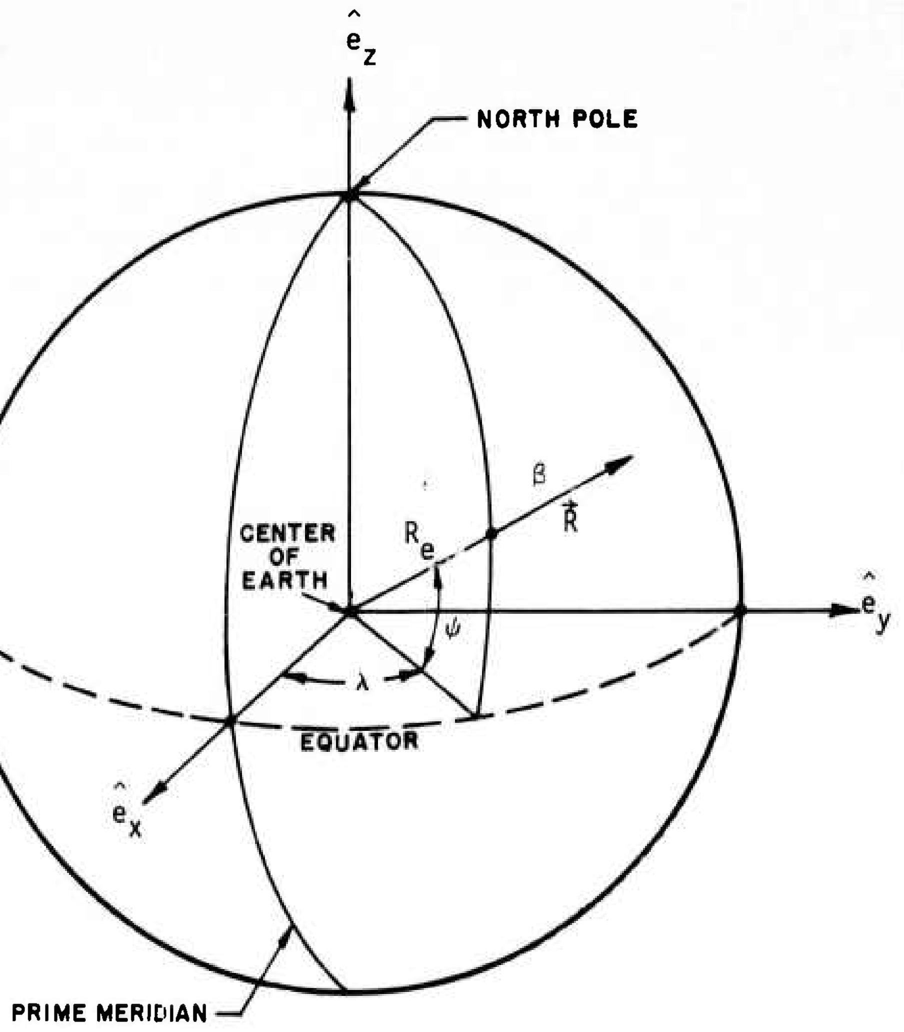


Figure 5. Earth-Fixed Coordinate System

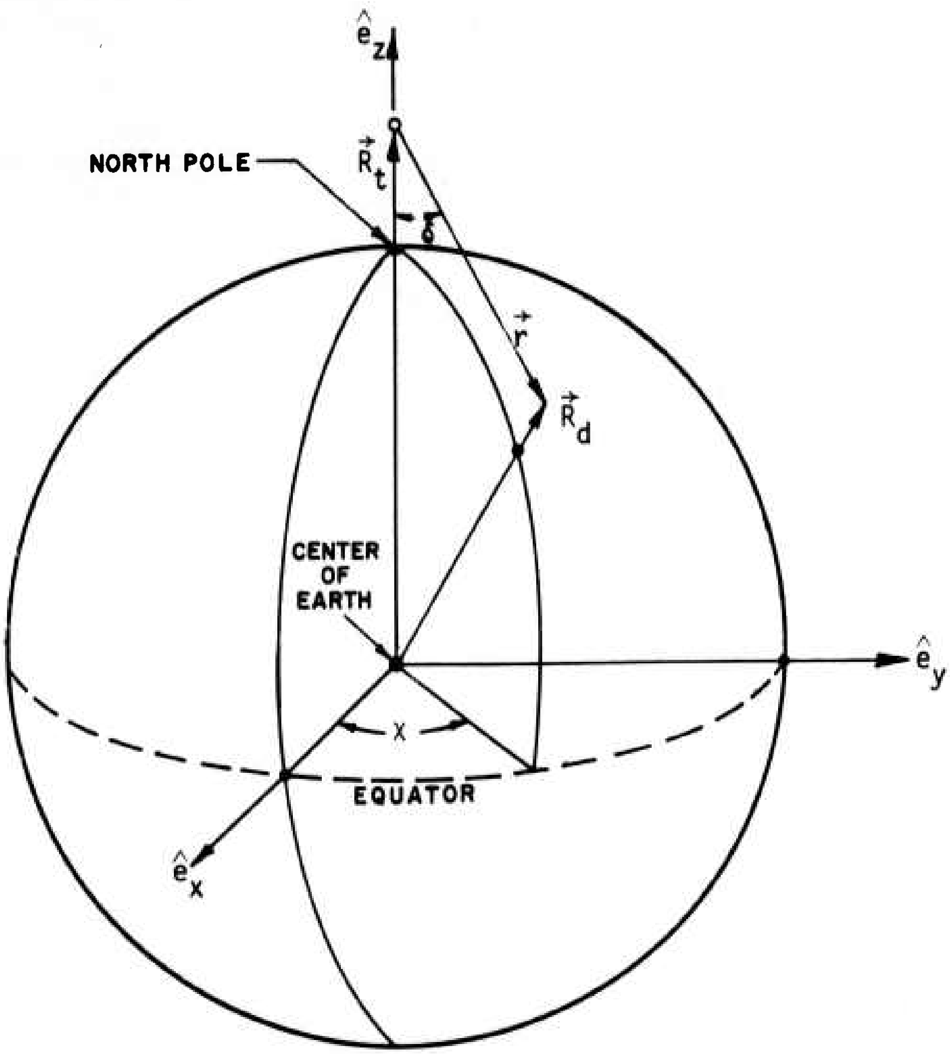


Figure 6. Alternative Earth-Fixed Coordinate System

As a simple check on the code, the projected area A_p of the target is also calculated. This may be written as:

$$A_p = \int \cos \phi \, dA \qquad \text{(IV-9)}$$

For computer evaluation, Eqs. IV-1 and IV-9 are converted to finite difference form:

$$I \cong \frac{\rho}{\pi} \sum_j \Delta A_j \cos \phi_j \sum_k \Delta E_k \cos \theta_{jk} \qquad \text{(IV-10)}$$

and

$$A_p \cong \sum_j \Delta A_j \cos \phi_j \qquad \text{(IV-11)}$$

where the only elements considered are those for which the cosine terms are positive.

C. INPUT/OUTPUT SPECIFICATIONS

Before DIFUS1 can be called, TARG and EARTH (in that order) must be requested by the user (see Appendixes I and II). As many calls as required may then be made to DIFUS1 without recalling the TARG and EARTH codes. Table 2 defines the input data necessary for using this code. The first data card provided for input to DIFUS1 must contain the letters DIF in the first three columns to indicate the operator desires to make a diffusely reflected signature calculation.

The output generated by DIFUS1 includes the following:

1. Projected area (sq mi)
2. View factor normalized to frontal projected area
3. View factor for radiation calculation normalized to projected area
4. Nadir angle (degrees)
5. Aspect angle (degrees)
6. Azimuth angle (degrees)
7. Radiant intensity (W/sr)

TABLE 2

INPUT DATA FOR DIFUS1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
TALT	β_T, target altitude normalized to radius of earth	dimen-sionless	$\geq 1.$	1.125	1.125
TLAT	ψ_T, target latitude	degrees	-90. to +90. if ND > 0, TLAT $\equiv$ 90.	90.	90.
TLON	λ_T, target longitude	degrees	0. to 360.	0.	0.
D	δ, nadir angle if ND = 1	degrees	0. to 180.	0.	0.
AZ	χ, azimuth angle if NAZ = 1 and ND > 0	degrees	0. to 180.	0.	0.
ND	Number of δ's to be calculated	dimen-sionless	≥ 0	0	0
NAZ	Number of χ's to be calculated	dimen-sionless	≥ 0	0	0
DI	Initial δ to be calculated, if ND > 1	degrees	$\geq 0.$, $<180.$	0.	0.
DF	Final δ to be calculated, if ND > 0	degrees	$>0.$, $\leq 180.$	180.	180.
AZI	Initial χ to be calculated, if ND > 0 and NAZ > 1	degrees	$>0.$, $<180.$	0.	0.
AZF	Final χ to be calculated, if ND > 0 and NAZ > 1	degrees	$>0.$, $\leq 180.$	180.	180.

TABLE 2 (Cont.)

INPUT DATA FOR DIFUS1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
E	Components of $\hat{i}$ from EARTH	dimen-sionless	$-1. \le E \le 1.$	N.A.	N.A.
XT, YT, ZT	Components of $\vec{R}_t$ from EARTH	dimen-sionless	N.A.	N.A.	0, 0, 1.125
H	Irradiance of elements from EARTH (with minus sign)	dimen-sionless	Usually nor-malized to unity	N.A.	-1.
NT	Number of input values (for $\hat{n}$) from TARG	dimen-sionless	$3 \le NT \le 7000$	N.A.	N.A.
XN, YN, ZN	Orientation unit vector of target from TARG	dimen-sionless	N.A.	N.A.	0., 0., -1.
T	Components of $\vec{A}$ from TARG	m^2	N.A.	N.A.	N.A.
APF	Front projected areas of target	cm^2	N.A.	100.	100.
RHO	Reflectance of target	dimen-sionless	$0 \le RHO \le 1$	1	0.-1.

TABLE 2 (Cont.)
INPUT DATA FOR DIFUS1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
ESN	Earthshine radiance, use only if no T9 put in EARTH	$W/sr/m^2$	N.A.	1.	N.A.
VALT	β, detector altitude normalized to radius of earth	dimensionless	$\geq 1.$	1.01	1.01
VLAT	ψ, detector latitude	degrees	-90. to +90.	0.	0.
VLON	λ, detector longitude	degrees	0. to 360.	0.	0.
WRITE	Control parameter. If = 0, writes no intermediate results. If = 1, writes intermediate results for debug purposes	dimensionless	1. or 0.	0.	0.
NE, NEH	Number of input values (for $\hat{i}$) from EARTH	dimensionless	$3 \leq NE \leq 3600$	N.A.	N.A.

V. CODE FOR DIRECTIONALLY EMITTED AND BIDIRECTIONALLY REFLECTED RADIATION FROM TARGETS (TINTF)

A. INTRODUCTION

This computer code is designed to calculate the directionally emitted radiation plus the bidirectionally reflected earthshine component of the optical radiation signature of an exoatmospheric target. The general procedure is to subdivide the target and the portion of the earth illuminating it into elemental areas. The emitted radiant intensity in the direction of the viewer is calculated using input directional emissivity. The reflected earthshine in the direction of the viewer is calculated using a double numerical integration considering the earth and target elements behave as flat plates. The bidirectional reflectivity is calculated using a semi-empirical technique that requires the refractive index absorption coefficient, and normal diffuse reflectance for the material as well as a measured distribution function for specular reflectance. Input tables calculated by other codes EARTH (Appendix II) and TARC (Appendix I) are required, so the assumptions implicit in them are also pertinent here.

B. DEVELOPMENT OF EQUATIONS

The radiant intensity of an incremental area of dA of the target emitted toward a detector can be written as:

$$dI = \varepsilon(\theta)\ dA \cos\theta \qquad \text{(V-1)}$$

where ε (θ) is the directional emittance of the material. To find the total emitted radiant intensity, this expression is integrated over all the target which is visible to the detector. The angle θ indicated in Fig. 3 is determined as follows:

$$\vec{R} = \vec{V} - \vec{T} \qquad \text{(V-2)}$$

$$\cos\theta = \vec{R} \cdot \hat{n}/R1 \qquad \text{(V-3)}$$

where $\hat{n}$ is the normal to the target element R1 is the magnitude of $\vec{R}$ and is obtained from

$$R1 = \sqrt{R_x^2 + R_y^2 + R_z^2} \qquad \text{(V-4)}$$

where R_x, R_y, and R_z are the components of $\vec{R}$ in an earth fixed coordinate system.

If θ is greater than 90°, there is no radiation to the viewer. The program also checks for earth blockage of the radiation from the target to the viewer by calculating the angle between a vector from the viewer to the center of the earth and from the target element to the viewer. This angle is used to calculate the length of a normal vector to the $\vec{R}$ vector to the center of the earth. If either ϕ is greater than 90° or $\vec{R}$ is greater than the radius of the earth, or if δ is less than α, there is no earth blockage (Fig. 7).

The radiant intensity of an incremental area dA of the target bi-directionally reflecting irradiance dE from an earth element, toward a detector (Fig. 8) can be written as:

$$dI = \rho(\psi,\ \theta,\ \phi)\ dE \cos\psi\ dA \cos\theta \qquad \text{(V-5)}$$

where $\rho(\phi, \theta, \phi)$ is the directional reflectivity. To find the total reflected radiant intensity, this expression is integrated over all the earth that is illuminating the target and over all the target that is visible to the detector. The angle θ has been determined previously. The angle ψ is obtained from:

$$\hat{n} \cdot \hat{e} = \cos\psi \qquad \text{(V-6)}$$

The angle ϕ is obtained as follows:

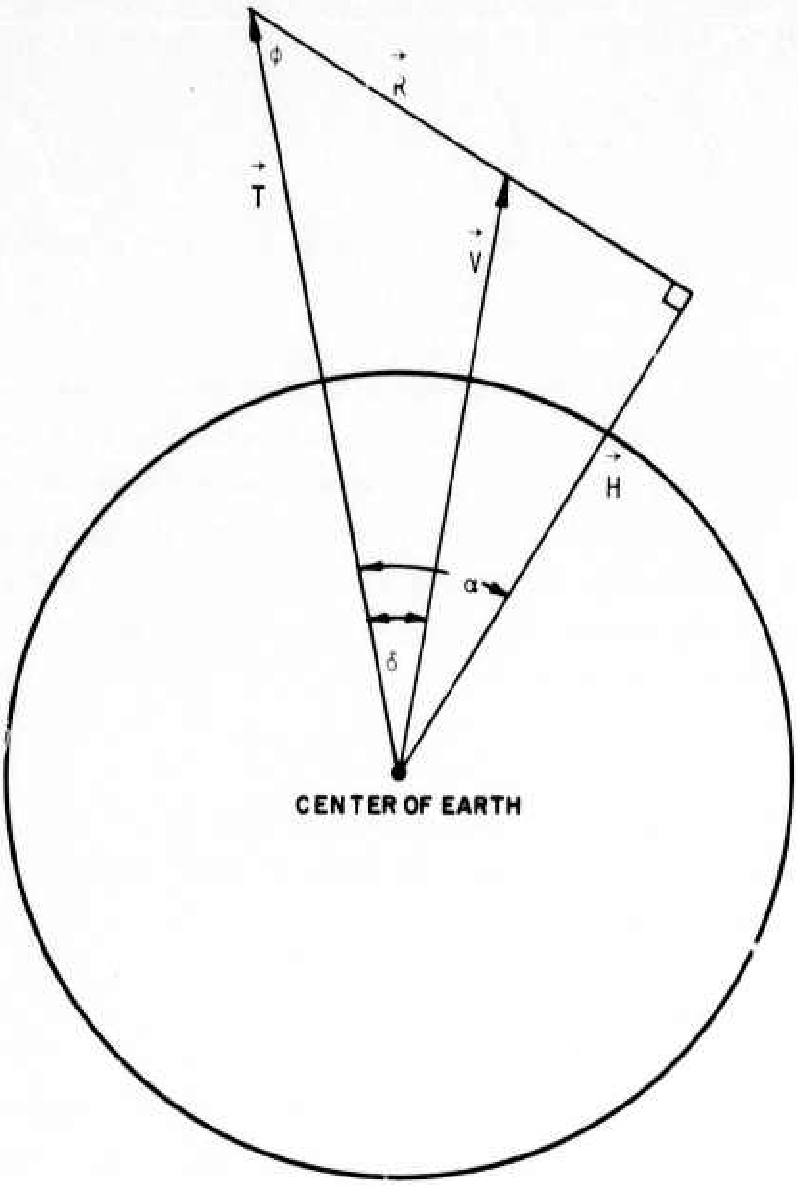


Figure 7. Earth Blockage Check

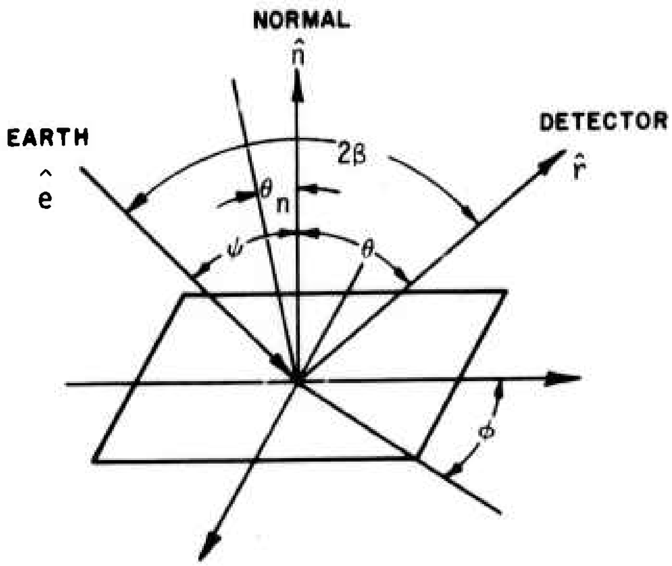


Figure 8. Bidirectional Reflectance

A vector $\hat{d}$ is determined by the relationship (see Fig. 8):

$$\hat{r} \times \hat{n} = \hat{d} \tag{V-7}$$

A vector $\hat{c}$ is determined from the relationship (see Fig. 8):

$$\hat{e} \times \hat{n} = \hat{c} \tag{V-8}$$

The angle ϕ is then obtained from the relationship:

$$\cos \phi = \hat{c} \cdot \hat{d} \tag{V-9}$$

The reflectivity is obtained from the following relationship:

$$\rho(\theta, \psi, \phi) = \rho^s(\theta_n) * \cos^2 \theta_n * \frac{\rho_L^s + \rho_P^s}{2 \cos \psi \cos \theta \dfrac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}} + \rho^d \tag{V-10}$$

where $\rho^s(\theta_n)$ is the directional specular reflectance (θ_n is indicated in Fig. 8)

ρ_L^s, ρ_P^s are the Fresnel reflectances calculated using β in Fig. 8

n is the material refractive index

κ is the material absorption coefficient

ρ^d is the diffuse reflectance of the material

C. INPUT/OUTPUT SPECIFICATION

Before TINTF can be called, TARG and EARTH (in that order) must be requested by the user (see Appendixes I and II). As many calls as required may then be made to TINTF without recalling the TARG and EARTH codes.

Table 3 defines the necessary input data for using this code. The first data card provided for input to TINTF must contain the letters TIN in the first three columns to indicate the operator desires to make a calculation using this code. The output generated by TINTF follows:

1. Projected area of target as seen by viewer (sq mi)
2. Area of target as seen by both earth and viewer (sq mi)
3. Radiant intensity of target toward the viewer due to reflected earthshine, assuming a bidirectional reflectance of 1 (W/sr)
4. Quantity needed to determine target emitted radiant intensity to the viewer
5. Bidirectional reflected earthshine radiant intensity in the direction of the viewer (W/sr)
6. Bidirectional target-reflected earth-reflected sunlit radiant intensity in direction of the viewer (W/sr)
7. Total overall wavelengths of emitted radiant intensity of objects in direction of viewer (W/sr)
8. Reflected radiant intensity in direction of viewer (W/sr)
9. Irradiance at target due to earthshine
10. Irradiance at target due to reflected sunlight
11. Sigma temperature to the fourth power (W/sr-cm^2)
12. Sum of total emitted and reflected radiant intensity (this is useful only when reflected signature is a total overall wavelength)
13. Temperature (K)

If only target-emitted radiant intensity is desired, set NOREFL equal to 1, and only target equilibirum temperature and effective emissivity in the direction of the viewer are calculated. To obtain the emitted radiant intensity in a specific wavelength interval, the output temperature and effective emissivity must be put into HRAD (Appendix III) and the result then added to the reflected component. The HRAD code is not, at present, a part of the exoatmospheric code and must be called individually through the OSC driver program.

TABLE 3

INPUT DATA FOR TINTF

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Values Used if Not Set	Typical Values
VALT	Detector altitude normalizing to radius of earth	dimen-sionless	$\geq 1.$	1.01	1.01
VLAT	Detector latitude	degrees	-90. to +90.	0.	0.
VLON	Detector longitude	degrees	0. to 360.	0.	0.
WRITE	Control parameter. If = 0, writes no intermediate print-outs. If = 1, writes inter-mediate printouts for debug purposes.	dimen-sionless	1. or 0.	0.	0.
NOREFL	Control parameter. If=1, no reflected earthshine cal-culated. If=0, earthshine calculated	dimen-sionless	1 or 0	0	0
NR	Number of THETANs and RHONs which are inputted	dimen-sionless	N.A.	N.A.	8
XN1	Refractive index	dimen-sionless	N.A.	N.A.	N.A.

TABLE 3 (Cont.)
INPUT DATA FOR TINTF

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Values Used if Not Set	Typical Values
XK	Absorption coefficient	dimen-sionless	N.A.	N.A.	N.A.
RD	Diffuse reflectance	dimen-sionless	0.1-1.0	N.A.	.3
RHON THETAN	Directional specular reflectance and corresponding angle	dimen-sionless degrees	0.0-1.0 0.-90.	N.A.	0.1, 0.2, 0.1, 0.3 109., 20., 40., 80.
NRP	Number of PTR's and ε's which are inputted	dimen-sionless	N.A.	N.A.	8
E, PTR	Directional emissivity and corresponding angle	dimen-sionless	0.1-1.0 0.-90.	N.A.	0.1, 0.2, 0.1, 0.1, 10., 20., 40., 80.
ASAT	Projected area as seen by the sun/total surface area	dimen-sionless	N.A.	0.25	N.A.
AEAT	Projected area as seen by earth/total surface area	dimen-sionless	N.A.	0.25	N.A.
AOE	Absorbtivity in the visible wavelengths/emissivity in the infrared wavelengths	dimen-sionless	N.A.	1.0	N.A.

TABLE 3 (Cont.)
INPUT DATA FOR TINTF

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Values Used if Not Set	Typical Values
GS	Solar radiation	$W/sr/m^2$	N.A.	0.14	N.A.
ESN	Earth radiation	$W/sr/m^2$	N.A.	1.0	N.A.

VI. DIRECTIONAL PROPERTIES EFFECT CODE (DIREC)

A. INTRODUCTION

Computer code DIREC was designed to determine the effect of directionality in the optical properties on the optical signatures of certain targets. These signatures are comprised of both self emitted and reflected earthshine so that both the emissivity and the reflectivity are required. Fresnel equations are employed to evaluate the optical properties. The calculated parameters from this code are total effective emissivity and reflectivity as a function of the viewer-target-earth geometry. Two simplifying assumptions were made in this code: uniform temperature and optical properties over the surface of the target and uniform earth radiance distribution. Either of these could be relaxed with little conceptual difficulty but the complexity of the code would be increased considerably.

Options are provided for inputting either the viewer position (in latitude, longitude, and altitude), or the viewer nadir and azimuth angles relative to the target. Results of another code TARG (Appendix I) are required, so the assumptions implicit in it are also pertinent here.

B. DEVELOPMENT OF EQUATIONS

If the viewer latitude (ψ_V), longitude (λ_V) and normalized altitude (β_V) are specified, the components of the viewer position vector $\vec{V}$ are found from:

$$x_V = \beta_V \cos \psi_V \cos \lambda_V$$

$$y_V = \beta_V \cos \psi_V \sin \lambda_V$$

$$z_V = \beta_V \sin \psi_V$$

These components are referenced to an earth-fixed, right-handed coordinate system with the origin at center of the earth, the z-axis toward the North Pole and the x-axis toward the prime meridian (see Fig. 9). Similarly for the target position vector $\vec{T}$:

$$x_T = \beta_T \cos \psi_T \cos \lambda_T$$

$$y_T = \beta_T \cos \psi_T \sin \lambda_T$$

$$z_T = \beta_T \sin \psi_T$$

The range vector $\vec{R}$ from the target to the viewer is simply the difference of these two:

$$\vec{R} = \vec{V} - \vec{T}$$

For the option of specifying the viewer nadir δ and azimuth χ angles, the target must be located along the z-axis and the target's axis in the x-z plane (see Fig. 10). Here different equations are used to determine $\hat{R}$:

$$R_x = \sin \delta \cos \chi$$

$$R_y = \sin \delta \sin \chi$$

$$R_z = -\cos \delta$$

TARG (Appendix I) provides area normal vector ($\vec{A}$) components from each target element in the same coordinate frame. The area an element projects toward the viewer (A_p) is (see Fig. 11):

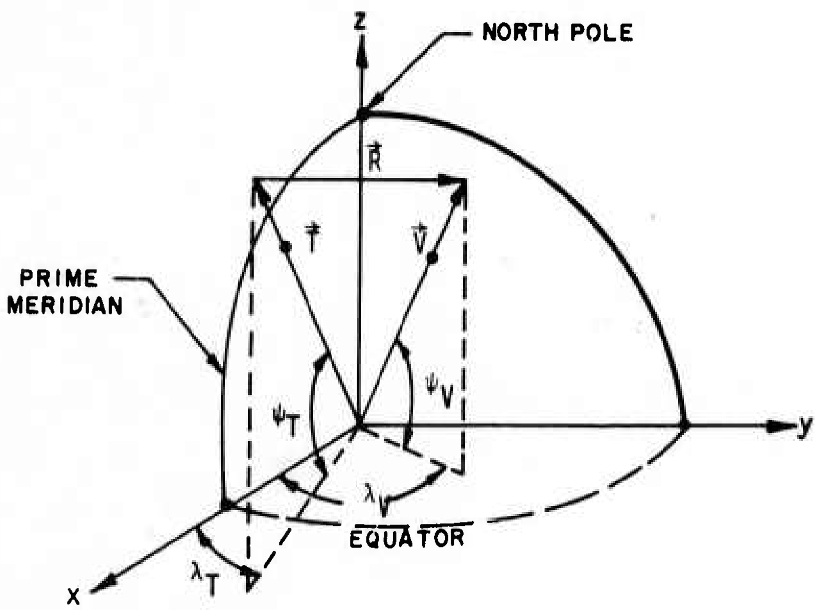


Figure 9. Viewer-Target-Earth Geometry

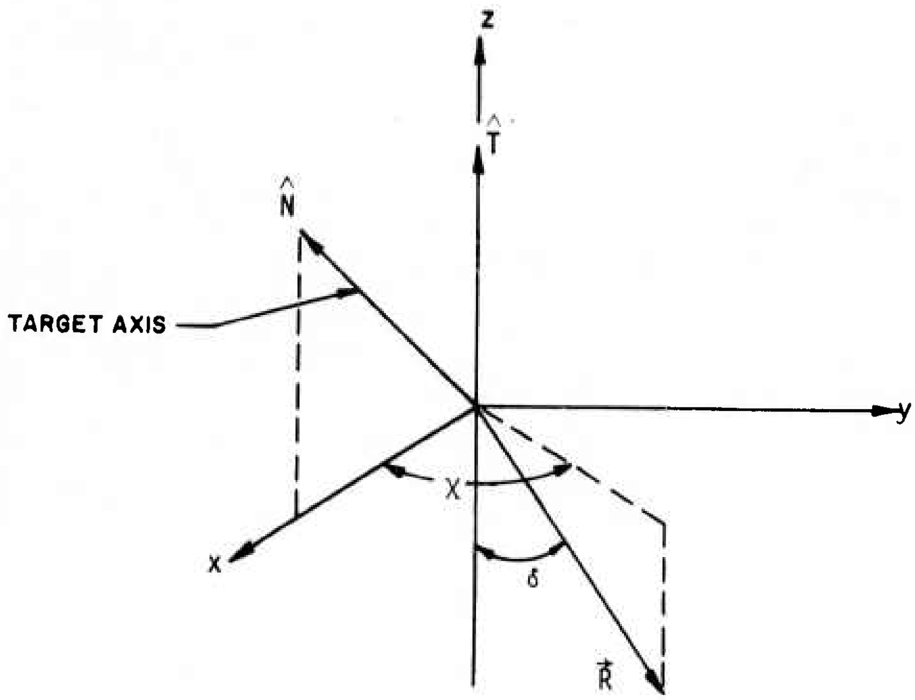


Figure 10. Viewer-Target-Earth Geometry, Target Along z-Axis

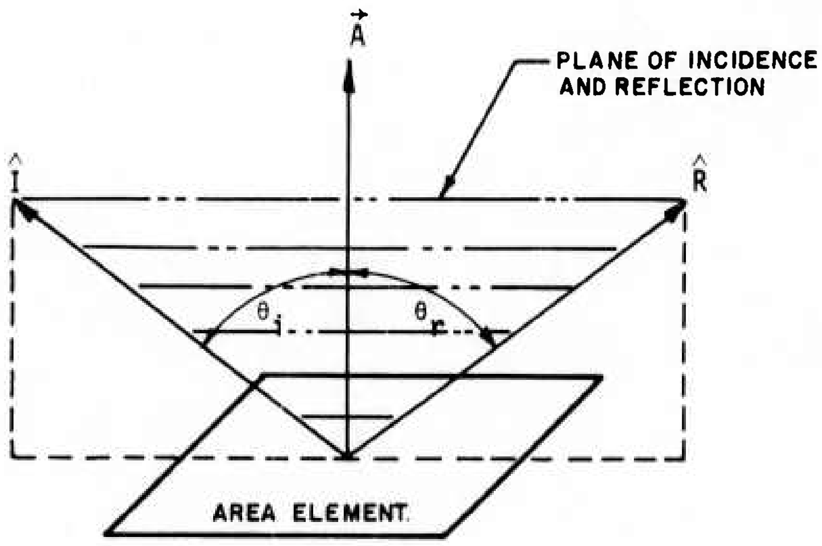


Figure 11. Reflection Geometry for an Elemental Area

$$A_p = \vec{A} \cdot \hat{R}$$

where $\hat{R}$ denotes a unitized vector obtained from:

$$\hat{R} = \vec{R}/|\vec{R}|$$

If this projected area is negative, the element faces away from the viewer and thus is neglected. The angle of reflection (θ_r), may be found from:

$$\cos \theta_r = A_p/|\vec{A}|$$

The Fresnel equations[19] give the reflectivities "ρ_L" and "ρ_P" inducing parallel "L" and perpendicular "P" polarization:

$$\rho_L = \frac{(n \cos \theta_r - \cos \chi)^2 + \kappa^2 \cos^2 \theta_r}{(n \cos \theta_r + \cos \chi) + \kappa^2 \cos^2 \theta_r}$$

$$\rho_P = \frac{(n \cos \chi - \cos \theta_r)^2 + \kappa^2 \cos^2 \chi}{(n \cos \chi + \cos \theta_r)^2 + \kappa^2 \cos^2 \chi}$$

where n is the refractive index and κ the extinction coefficient of the material, and:

$$\sin \chi = \frac{1}{n} \sin \theta_r$$

The unpolarized reflectivity ρ is simply the average of those:

$$\rho = \frac{\rho_L + \rho_P}{2}$$

and the emissivity "ε" (for an opaque material):

$$\varepsilon = 1 - \rho$$

Assuming the target's surface to be at a uniform temperature, the effective emissivity $\bar{\varepsilon}$ is simply:

$$\bar{\varepsilon} = \frac{1}{A_{p_t}} \sum_{i=1}^{N} \varepsilon_i A_{p_i} P(A_{p_i})$$

where N is the total number of elements, P is a function which is unity if its argument is positive and zero if nonpositive, and the total projected area A_{p_t} is:

$$A_{p_t} = \sum_{i=1}^{N} A_{p_i} P(A_{p_i})$$

The effective reflectivity $\bar{\rho}$ is similarly expressed assuming the earthshine to have a uniform spatial distribution:

$$\bar{\rho} = \frac{1}{A_r} \sum_{i=1}^{N} \rho_i A_{p_i} P(A_{p_i}) P(\beta_i')$$

where the total reflecting area A_r is defined by:

$$A_r = \sum_{i=1}^{N} A_{p_i} P(A_{p_i}) P(\beta_i')$$

The function $P(\beta_i')$ indicates whether the ith element actually reflects the earth's image to the viewer. The argument β' is defined:

$$\beta' = \phi_m - \beta$$

where ϕ_m is the nadir angle to the earth's horizon and β is the angle between the nadir position and a unit vector $\hat{I}$ indicating the incidence direction (see Fig. 12).

They are evaluated from

$$\cos \beta = -\hat{I} \cdot \hat{T}$$

and

$$\sin \phi_n = \frac{R_e}{R_e + H_t}$$

where R_e is the radius of the earth and H_t is the altitude of the target from the surface of the earth.

Since for total reflection, the angle of incidence θ_i equals the angle of reflection θ_r:

$$\hat{A} \times \hat{I} = \hat{R} \times \hat{A}$$

and

$$\hat{A} \cdot \hat{I} = \cos \theta_i$$

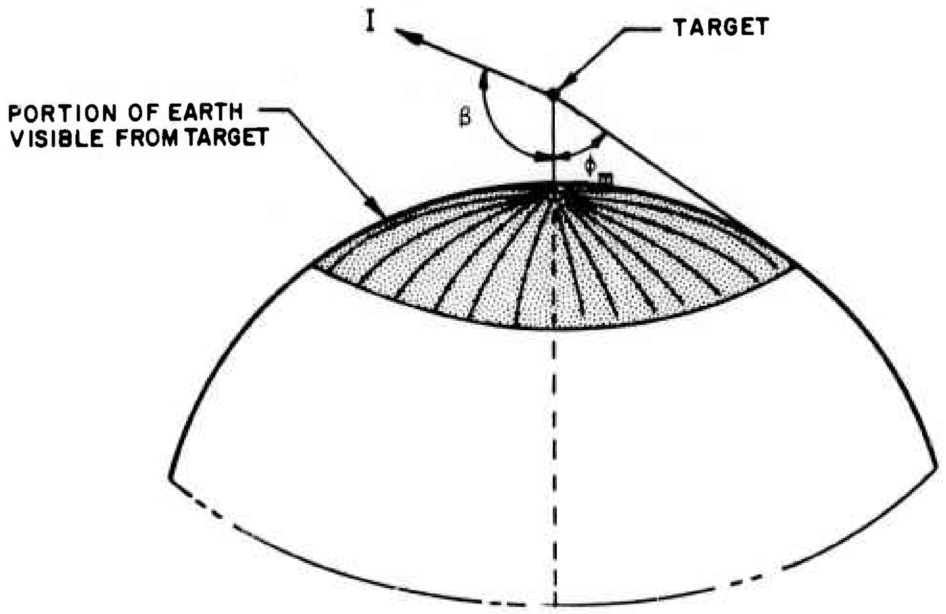


Figure 12. Reflection Geometry (Nadir Angle)

After expanding we get four equations (three are dependent) in the three unknown components of I, which may be solved to give:

$$I_x = A_x \cos\theta + C_2A_z + C_3A_y$$

$$I_y = A_y \cos\theta - C_1A_z - C_3A_x$$

$$I_z = A_z \cos\theta + C_1A_y - C_2A_x$$

where $C_1 \equiv A_zR_y - A_yR_z$

$C_2 \equiv A_xR_z - A_zR_x$

$C_3 \equiv (C_1A_x + C_2A_y)/A_z$

or if $A_z = 0$,

$$I_z = -R_z$$

$$C_3 \equiv A_zR_y - A_yR_x$$

Finally, the aspect angle θ (measured from nose on) is found from the vector specifying the target's axis $\hat{N}$ and the range vector $\hat{R}$:

$$\cos\theta = \hat{N} \cdot \hat{R}$$

C. INPUT/OUTPUT SPECIFICATIONS

Before DIREC can be called, TARG must be requested by the user (see Appendix I). As many calls as required may then be made to DIREC without recalling the TARG code. Table 4 defines the necessary input for using this code. The first data card provided for input to DIREC must contain the letters DIR in the first three columns to indicate the operator desires to use this code. The output generated by DIREC follows:

1. Projected area (sq mi)
2. Reflected area to projected area ratio ($\leq$ 1)
3. Effective reflectance of target ($\leq$ 1)
4. Effective emittance of target ($\leq$ 1)
5. Total radiant intensity (using Fresnel equations)
6. Total radiant intensity (assuming uniformity)
7. Aspect angle (degrees)
8. Error in using normal reflectance
9. Error in using normal emittance
10. Nadir angle (degrees)

TABLE 4
INPUT DATA FOR DIREC

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
TALT	β_T, target altitude normalized to radius of earth	dimensionless	$\geq 1.$	1.125	1.125
TLAT	ψ_T, target latitude	degrees	-90. to +90. if ND > 0, TLAT ≡ 90.	90.	90.
TLON	λ_T, target longitude	degrees	0. to 360.	0.	0.
D	δ, nadir angle if ND = 1	degrees	0. to 180.	0.	0.
AZ	ξ, azimuth angle if NAZ = 1 and ND > 0	degrees	0. to 180.	0.	0.
ND	Number of δ's to be calculated	dimensionless	≥ 0	0	0
NAZ	Number of ξ's to be calculated	dimensionless	≥ 0	0	0
DI	Initial δ to be calculated, if ND > 1	degrees	$\geq 0.$, $< 180.$	0.	0.
DF	Final δ to be calculated, if ND > 1	degrees	$\geq 0.$, $\leq 180.$	180.	180.

TABLE 4 (Cont.)
INPUT DATA FOR DIREC

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
AZI	Initial ξ to be calculated, if ND > 0 and NAZ > 1	degrees	$\geq 0.$, $<180.$	0.	N.A.
AZF	Final ξ to be calculated, if ND > 0 and NAZ > 1	degrees	$>0.$, $\leq 180.$	180.	N.A.
VALT	β_V, viewer altitude normalized to radius of earth	dimen-sionless	$\geq 1.$	1.01	1.01
VLAT	ψ_V, viewer latitude if ND $\leq$ 0	degrees	-90. to +90.	0.	0.
VLON	λ_V, viewer longitude	degrees	0. to 360.	0.	0.
XN, YN, ZN	Components of unit vector along target axis	dimen-sionless	if ND > 0, XN > 0	0.969, 0., -0.34.2	0.,0., -1.
N	n, index of refraction	dimen-sionless	$\geq 1.$	3.	3.
K	κ, absorption coefficient	dimen-sionless	$\geq 0.$	10.	10.

TABLE 4 (Cont.)

INPUT DATA FOR DIREC

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
WRITE	Control parameter. If = 0, writes no intermediate results. If = 1, writes intermediate results for debug purposes	dimen-sionless	1. or 0.	0.	0.
T	Components of $\vec{A}$ from TARG	m^2	N.A.	N.A.	N.A.
NT	Number of input values for $\hat{N}$ from TARG	dimen-sionless	$3 \leq NT < 7000$	N.A.	N.A.
RADE	Radiance of earth at target	dimen-sionless	N.A.	0.	N.A.
RADT	Blackbody radiance of target	dimen-sionless	N.A.	0.	N.A.

VII. CODE FOR POLARIZATION CONTENT OF TARGET EMISSION SIGNATURE (EP1)

A. INTRODUCTION

Computer code EP1 was designed to calculate the polarization content of the emission component of a target's optical signature. Input tables from the computer code TARG (Appendix I) are required, so assumptions implicit in it are pertinent here. The general procedure is to (1) subdivide the target into elemental areas, (2) determine the two components of polarized emissivity for a general element, (3) reference these components to a plane independent of the particular element, and (4) integrate over the portion of the target exposed to the detector. It is assumed that these elements may be considered flat planes and that the target is small relative to its range from the detector.

B. DEVELOPMENT OF EQUATIONS

If the latitude ψ, longitude λ, and altitude β (normalized to the radius of the earth) of the target (denoted by subscript t) and of the detector (subscript d) are given, their position vectors $\vec{R}$ may be written with respect to the earth-fixed coordinate system shown in Fig. 13, as:

$$\vec{R}_t = \beta_t(\hat{e}_x \cos\psi_t \cos\lambda_t + \hat{e}_y \cos\psi_t \sin\lambda_t + \hat{e}_z \sin\psi_t) \quad \text{(VII-1)}$$

$$\vec{R}_d = \beta_d(\hat{e}_x \cos\psi_d \cos\lambda_d + \hat{e}_y \cos\psi_d \sin\lambda_d + \hat{e}_z \sin\psi_d) \quad \text{(VII-2)}$$

and the vector from the target to the detector is simply:

$$\vec{r} = \vec{R}_t - \vec{R}_d \quad \text{(VII-3)}$$

and

$$\hat{r} = \vec{r}/|\vec{r}| \quad \text{(VII-4)}$$

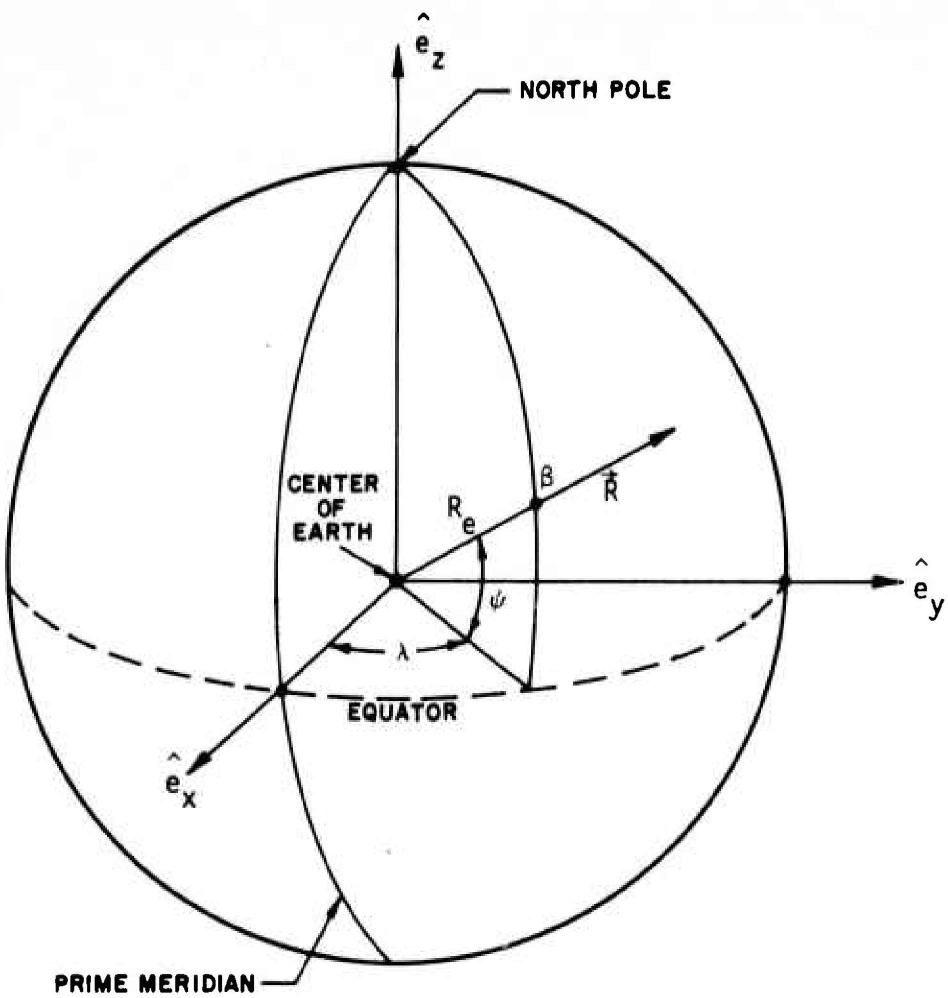


Figure 13. Earth-Fixed Coordinate System

Alternatively, if the nadir angle δ and the azimuth angle χ to the viewer relative to the target are specified (see Fig. 14) we can write simply:

$$\hat{r} = \hat{e}_x \sin\delta \cos\chi + \hat{e}_y \sin\delta \sin\chi - \hat{e}_z \cos\delta \qquad \text{(VII-5)}$$

where the target is located on the z axis.

Consider an arbitrary element of the target whose size and orientation is specified by a normal vector $\vec{A}$. The polarized components of radiant intensity from this element are:

$$\begin{aligned} dI_P &= \varepsilon_P N_{BB}\, dA \cos\theta \\ dI_L &= \varepsilon_L N_{BB}\, dA \cos\theta \end{aligned} \qquad \text{(VII-6)}$$

where ε_P and ε_L are the parallel and perpendicular polarization sensitive emissivities, respectively, N_{BB} is the blackbody radiance of the element, dA is the area of the element and θ is the angle between the element's normal vector $\vec{r}$. Using vector algebra, the angle θ is given by:

$$\cos\theta = \hat{r} \cdot \hat{A} \qquad \text{(VII-7)}$$

Using this angle, theoretical polarized emissivities ε_P and ε_L are calculated by Fresnel equations. This polarization is defined with respect to the plane of incidence of the particular target element being considered and so must be referenced to a common plane. If ϕ is the angle between the plane of incidence (whose unit normal is $\hat{M}$) and an arbitrary reference plane containing $\vec{r}$ (whose unit normal is $\hat{P}$), the polarization components of radiant intensity with respect to the equatorial plane are simply:

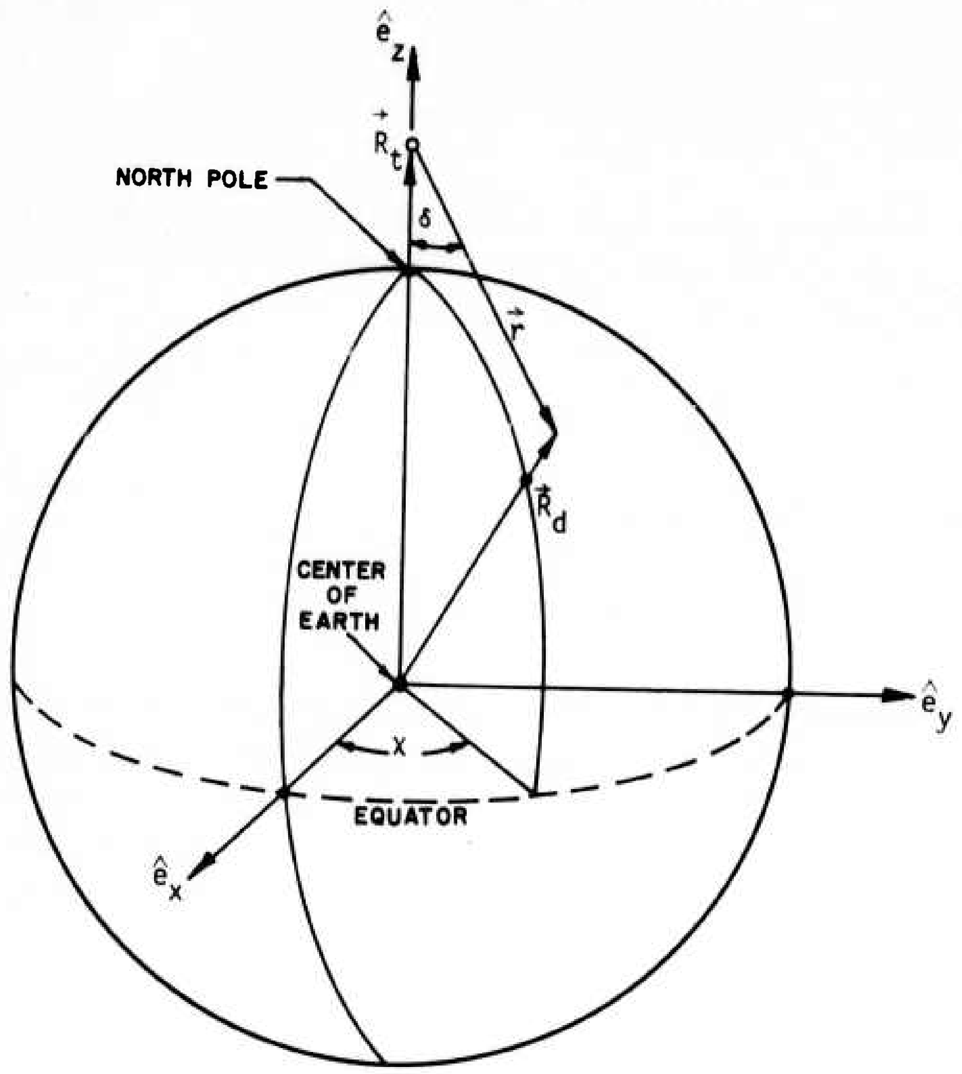


Figure 14. Alternative Earth-Fixed Coordinate System

$$dI'_P = dI_P \cos^2 \phi + dI_L \sin^2 \phi$$

$$dI'_L = dI_P \sin^2 \phi + dI_L \cos^2 \phi \qquad \text{(VII-8)}$$

Note that since the sine and cosine functions are squared, it does not matter whether the angle ϕ or its supplement $(\pi - \phi)$ is used. From vector algebra

$$\cos \phi = \hat{M} \cdot \hat{P} \qquad \text{(VII-9)}$$

where $\vec{M}$ may be written as:

$$\vec{M} = \vec{A} \times \hat{r} \quad \text{and} \quad \hat{M} = \vec{M}/|\vec{M}| \qquad \text{(VII-10)}$$

As an additional check on the calculation, an option is included to allow selection of any reference plane (which includes $\vec{r}$). The control parameter is NREF where, if NREF = 1, the plane is defined by vectors $\vec{r}$ and $\vec{R}_t$, or, if NREF > 1, the vectors $\vec{r}$ and $\vec{Q}$ are used ($\vec{Q}$ is an arbitrary vector to be set). Thus the reference plane's normal vector is:

$$\vec{P} \equiv \vec{R}_t \times \vec{r} \quad \text{if} \quad \text{NREF} \leq 1 \qquad \text{(VII-11)}$$

or

$$\vec{P} \equiv \vec{Q} \times \vec{r} \quad \text{if} \quad \text{NREF} > 1 \qquad \text{(VII-12)}$$

For computer evaluation, Eqs. VII-6 with Eq. VII-8 are converted to finite difference form, numerically integrated, and normalized with respect to N_{BB} and A_p:

$$\varepsilon_P' = \sum_i \Delta A_i \cos\theta_i \, (\varepsilon_P \cos^2\phi + \varepsilon_L \sin^2\phi)/A_p \qquad \text{(VII-13)}$$

$$\varepsilon_P' = \sum_i \Delta A_i \cos\theta_i \, (\varepsilon_P \sin^2\phi + \varepsilon_L \cos^2\phi)/A_p \qquad \text{(VII-14)}$$

Finally, these results are expressed in terms of a parameter commonly used as a measure of the polarization:

$$\varepsilon_P \equiv \frac{\varepsilon_P' - \varepsilon_L'}{\varepsilon_P' + \varepsilon_L'} \qquad \text{(VII-15)}$$

It is seen that ε_P is independent of the target temperature if the target is assumed isothermal, (i.e., N uniform).

As a simple check on the code, the projected area A_p of the target is also calculated. This may be written as:

$$A_p = \int \cos\theta \, dA \qquad \text{(VII-16)}$$

and

$$A_p \simeq \sum_i \Delta A_i \cos\theta_i \qquad \text{(VII-17)}$$

where the only elements considered are those for which the cosine terms are positive.

C. INPUT/OUTPUT SPECIFICATIONS

Before EP1 can be called, TARG must be requested by the user (see Appendix I). As many calls as required may then be made to EP1 without recalling the TARG code. Table 5 defines the input necessary for using this code. The first data card provided for input to EP1 must contain the letters EP1 in columns one through three to indicate the operator desires to use this code. The output generated by EP1 follows:

1. Aspect angle (degrees)
2. Nadir angle (degrees)
3. Azimuth angle (degrees)
4. Projected area (sq mi)
5. Degree polarized
6. Parallel polarization
7. Perpendicular polarization

TABLE 5
INPUT DATA FOR EP1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
TALT	β_t, target altitude normalized to radius of earth	dimen-sionless	$\geq 1.$	1.125	1.125
TLAT	ψ_t, target latitude	degrees	-90. to +90. if ND > 0, TLAT ≡ 90.	90.	90.
TLON	λ_t, target longitude	degrees	0. to 360.	0.	0.
D	δ, nadir angle if ND = 1	degrees	0. to 180.	0.	0.
AZ	χ, azimuth angle if NAZ = 1 and ND > 0	degrees	0. to 180.	0.	0.
ND	Number of δ's to be calculated	dimen-sionless	≥ 0	0	0
NAZ	Number of χ's to be calculated	dimen-sionless	≥ 0	0	0
DI	Initial δ to be calculated, if ND > 1	degrees	$\geq 0.$, $<180.$	0.	0.

TABLE 5 (Cont.)
INPUT DATA FOR EP1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
DF	Final δ to be calculated, if ND > 0	degrees	>0., $\leq$180.	180.	180.
AZI	Initial χ to be calculated, if ND > 0 and NAZ > 1	degrees	$\geq$0., <180.	0.	0.
AZF	Final χ to be calculated, if ND > 0 and NAZ > 1	degrees	>0., $\leq$180.	180.	180.
VALT	β, detector altitude normalized to radius of earth (if ND $\leq$ 0)	dimensionless	$\geq$1.	1.01	1.01
VLAT	ψ, detector latitude (if ND $\leq$ 0)	degrees	-90. to +90.	0.	0.
VLON	λ, detector longitude (if ND $\leq$ 0)	degrees	0. to 360.	0.	0.
WRITE	Control parameter. If = 0, writes no intermediate results. If = 1, writes intermediate results for debug purposes	dimensionless	1. or 0.	0.	0.

TABLE 5 (Cont.)

INPUT DATA FOR EP1

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
NETOT	Number of input values (for $\hat{n}$) from TARG	dimen-sionless	$3 \leq$ NETOT ≤ 7000	N.A.	N.A.
XN, YN, ZN	Orientation unit vector of target from TARG	dimen-sionless	N.A.	N.A.	0., 0., -1.
T	Components of $\vec{A}$ from TARG	m^2	N.A.	N.A.	N.A.
N	n index of refraction	dimen-sionless	$\geq 1.$	3.	3.
K	κ, absorption coefficient	dimen-sionless	$\geq 0.$	10.	10.
NREF	Control parameter to select reference plane for polarization. If = 1, uses vector R_t.	dimen-sionless	N.A.	1	1
XQ, YQ ZQ	Components of vector which, with vector F, defines the reference plane when NREF ≥ 1	dimen-sionless	N.A.	1., 0., 0.	1., 0., 0.

VIII. CODE FOR POLARIZATION CONTENT OF SPECULARLY REFLECTED EARTHSHINE (SPOL)

A. INTRODUCTION

This computer code is designed to calculate the polarization content of the specularly reflected component of a target's optical signature. Theoretical Fresnel expressions are used to provide the polarized reflectivities. Input tables calculated by TARG are required, so the assumptions implicit in this code are also pertinent here. The general procedure is to (1) subdivide the target into elemental areas, (2) determine the two components of polarized reflectivity for each element, (3) reference these components to a plane independent of the particular element, and (4) integrate over the portion of the target exposed to the detector that will specularly reflect earthshine. It is assumed that these elements may be considered flat plates and that the target is small relative to its range from the detector.

B. DEVELOPMENT OF EQUATIONS

The polarized components of radiant intensity of an incremental area dA of the target specularly reflecting radiance $L_\lambda(\phi)$ from an earth element, toward a detector (Fig. 3) can be written:

$$dI_L = \rho_L^s L_\lambda(\phi)\ dA \cos\theta \qquad \text{(VIII-1)}$$

$$dI_P = \rho_P^s L_\lambda(\phi)\ dA \cos\theta \qquad \text{(VIII-2)}$$

where ρ_P^s and ρ_L^s are the parallel and perpendicular polarization sensitive reflectivities, respectively.

To obtain the total polarized radiant intensity due to reflected earthshine, this expression is integrated over all the target that is visible to the detector and from which specular reflection from the earth is possible.

The angle θ is defined in Fig. 3 and is determined as follows:

$$\vec{R} = \vec{V} - \vec{T} \tag{VIII-3}$$

$$\cos\,\theta = R \cdot \hat{n}/R1 \tag{VIII-4}$$

where $\hat{n}$ is the normal to the target element and R1 is the magnitude of $\vec{R}$ and is obtained from

$$R1 = \left(R_x^2 + R_y^2 + R_z^2\right)^{1/2} \tag{VIII-5}$$

where R_x, R_y, and R_z are the components of $\vec{R}$ in an earth fixed coordinate system.

If θ is greater than 90°, there is no radiation to the viewer. When θ is less than 90°, one must for each element determine the vector $\hat{i}$ and ensure that it intersects the earth. Three independent equations are required in order to determine the three components of $\hat{i}$. Two independent equations are determined from the relationship (Fig. 3)

$$\hat{n} \times \hat{r} = \hat{i} \times \hat{n} \tag{VIII-6}$$

and the third from the relationship

$$\hat{r} \cdot \hat{n} = \hat{n} \cdot \hat{i} \tag{VIII-7}$$

To ensure that the vector $\hat{i}$ intersects the earth, the angle β (Fig. 3) is calculated from the relationship

$$\hat{T} \cdot \hat{i} = \cos\,\theta \tag{VIII-8}$$

If $\beta < \phi$, where ϕ = arc sin (earth radius/earth radius and target altitude), then the vector $\hat{i}$ intersects the earth and the element contributes to the specularly reflected radiant intensity of the target.

The polarization-sensitive reflectivities are determined from Fresnel's equations with respect to the plane of incidence of the particular target element being considered and must be referenced to a common plane.

The common plane is the plane determined by the vector from the center of the earth to the target and the vector from the center of the earth to the detector. If these vectors are collinear, the common plane is determined by these vectors and the vector from the center of the earth through the North Pole. If all three of these vectors are collinear, the common plane is the plane determined by these vectors and a vector from the center of the earth through the equator at the Greenwich Meridian. The polarization components of radiant intensity with respect to the common plane is simply

$$dI_L' = \left(dI_L\right) \cos^2 \phi + \left(dI_P\right) \sin^2 \phi \qquad \text{(VIII-9)}$$

$$dI_P' = \left(dI_L\right) \sin^2 \phi + \left(dI_P\right) \cos^2 \phi \qquad \text{(VIII-10)}$$

where ϕ is the angle between the plane of incident and reflected radiation and the common plane. Note that since the sine and cosine functions are squared, it does not matter whether the angle ϕ or its supplement $(\pi - \phi)$ is used. From vector algebra

$$\cos \phi = \hat{m} \cdot \hat{p} \qquad \text{(VIII-11)}$$

where

$$\hat{m} = \hat{r} \times \hat{n} \tag{VIII-12}$$

and p is the unit normal vector to the reference plane.

$$\hat{p} = \hat{i} \times \hat{Q} \tag{VIII-13}$$

where $\hat{Q}$ is one of the three vectors indicated earlier.

For computer evaluation, Eqs. VIII-9 and VIII-10 with Eqs. VIII-1 and VIII-2 are converted to finite difference form, numerically integrated, and normalized with respect to $L_\lambda(\phi)$ and A_p:

$$I_L' = \sum_i \Delta A_i \cos\theta_i \left(\rho_L^s \cos^2\phi + \rho_P^s \sin^2\phi\right)/A_p \tag{VIII-14}$$

$$I_P' = \sum_i \Delta A_i \cos\theta_i \left(\rho_L^s \sin^2\phi + \rho_P^s \cos^2\phi\right)/A_p \tag{VIII-15}$$

Finally these results are expressed in terms of a parameter commonly used as a measure of the polarization:

$$\rho_P = \frac{I_L' - I_P'}{I_L' + I_P'} \tag{VIII-16}$$

As a check, the projected area (A_p) of the target is calculated. It is simply

$$A_p = \sum \Delta A_i \cos\theta_i \tag{VIII-17}$$

where the only elements considered are those for which the cosine terms are positive.

C. INPUT/OUTPUT SPECIFICATIONS

Before SPOL can be called, TARG must be requested by the user (see Appendix I). As many calls as required may then be made to SPOL without recalling the TARG code. Table 6 defines the input necessary for using this code. The first data card provided for input to SPOL must contain the letters SPO in the first three columns to indicate the operator desires to use this code. The output generated by SPOL follows:

1. Aspect angle (degrees)
2. Nadir angle (degrees)
3. Azimuth angle (degrees)
4. Projected area (sq mi)
5. Degree polarized
6. Parallel polarization
7. Perpendicular polarization

TABLE 6

INPUT DATA FOR SPOL

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
VALT	Detector altitude normalized to radius of earth	dimen-sionless	≥1.	1.01	1.01
VLAT	Detector latitude	degrees	-90. to +90.	0.	0.
VLON	Detector longitude	degrees	0. to 360.	0.	0.
WRITE	Control parameter. If = 0, writes no intermediate results. If = 1, writes intermediate results for debug purposes	dimen-sionless	1. or 0.	0.	0.
TALT	Target altitude normalized to radius of earth	dimen-sionless	≥1.	1.125	1.125

TABLE 6 (Cont.)
INPUT DATA FOR SPOL

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
TLON	Target longitude	degrees	0. to 360.	0.	0.
TLAT	Target latitude	degrees	-90. to +90.	90.	90.
D	Nadir angle	degrees	0. to 180.	0.	0.
ND	Control parameter for number of nadir angles. If ≤ 0, inputs viewer lat., long., and alt. If > 1, calculates output for ND nadir angles	dimensionless	N.A.	0	0
NAZ	Control parameter for number of azimuth angles to be calculated. If > 1, calculates output for NAZ azimuth angles.	dimensionless	N.A.	0	0
AZ	Azimuth angle	degrees	0. to 180.	0.	0.

TABLE 6 (Cont.)
INPUT DATA FOR SPOL

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
DI	If more than one nadir value is to be calculated, this is the first.	degrees	0. to 180.	0.	0.
DF	If more than one nadir angle is to be calculated, this is the last.	degrees	0. to 180.	180.	180.
AZI	If more than one azimuth angle is to be calculated, this is the first.	degrees	0. to 180.	0.	0.
AZF	If more than one azimuth angle is to be calculated, this is the last.	degrees	0. to 180.	180.	180.

TABLE 6 (Cont.)
INPUT DATA FOR SPOL

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
N	η, index of refraction	dimen-sionless	$\geq 1.$	N.A.	3.
K	κ, absorption coefficient	dimen-sionless	$\geq 0.$	N.A.	10.
NREF	Control parameter to select reference plane for polarization. If=1 $\vec{T}$ and $\vec{V}$ not collinear.	dimen-sionless	N.A.	1	1
XQ, YQ, ZQ	Component of vector needed to form reference plane if $\vec{T}$ and $\vec{V}$ are collinear and if NREF > 1.	dimen-sionless	N.A.	1., 0., 0.	1., 0., 0.
NT	Number of input values for $\hat{n}$ from TARG	dimen-sionless	$3 \leq NT \leq 7000$	N.A.	N.A.
XN, YN ZN	Orientation unit vector of target from TARG	dimen-sionless	N.A.	N.A.	0., 0., 1.
T	Components of $\vec{A}$ from TARG	m^2	N.A.	N.A.	N.A.

APPENDIX I

TARGET-ELEMENT CODE (TARG)

A. INTRODUCTION

This program is one of a series to be employed for calculating the radiant intensity of exoatmospheric targets. Its specific purpose is to determine the area normal vectors of elemental areas on the target. The components of these vectors are stored for use in subsequent codes. Only sphere-cone-shaped targets may be handled by this program. However, the dimensions and cone angles are adjustable so the shapes can include pure cones, hemispheres, and hemisphere-cylinders. The base of these targets is assumed to be a simple circular plate.

Position of the target must be supplied in terms of its latitude and longitude. The orientation of the target is specified by two other angles. Components of the required vectors are given in the earth-fixed coordinate system defined by the North Pole and Greenwich meridian.

B. DEVELOPMENT OF EQUATIONS

An earth-fixed Cartesian coordinate system (x, y, z) is defined by the origin at the center of the earth, the z-axis pointing north and the x-axis toward the Greenwich Meridian (all coordinate systems are right-handed). Components of the target position unit vector T_x, T_y, T_z (see Fig. 15) are given in terms of its longitude λ_T and its latitude ψ_T (positive in Northern Hemisphere, negative in Southern), by:

$$T_x = \cos \psi_T \cos \lambda_T$$

$$T_y = -\cos \psi_T \sin \lambda_T \qquad \text{(AI-1)}$$

$$T_z = \sin \psi_T$$

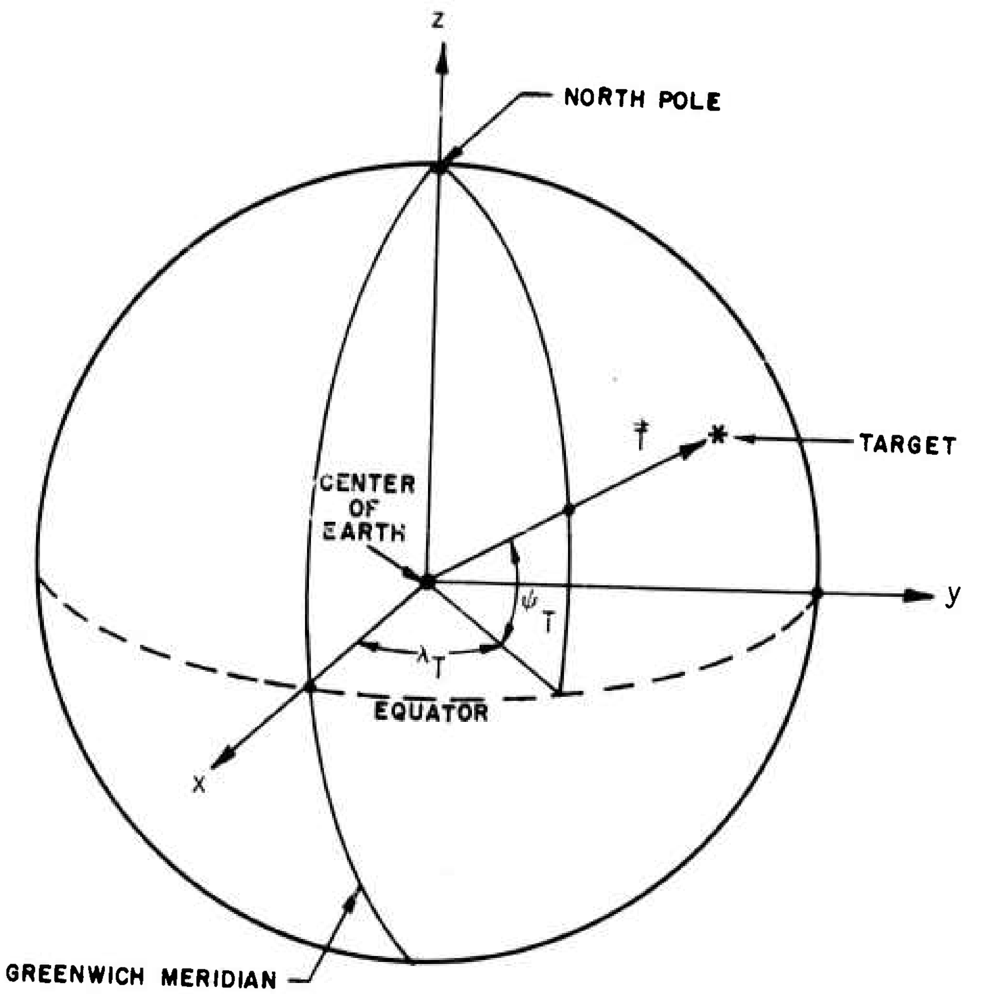


Figure 15. Earth-Fixed Coordinate System in Terms of Longitude and Latitude

A local coordinate system (x_1, y_1, z_1) is defined such that the x_1 axis is collinear with T_x and z_0 axis in the x_1-z_1 plane (see Fig. 16a). This transformation may be expressed by the following equations where x_1, y_1, z_1 are components of any vector in the local coordinate system and x_0, y_0, z_0 are components of the same vector in the earth-fixed system:

$$x = x_1 \cos \psi_T \cos \lambda_T - y_1 \sin \lambda_T - z_1 \sin \psi_T \cos \lambda_T$$

$$y = x_1 \cos \psi_T \sin \lambda_T + y_1 \cos \lambda_T - z_1 \sin \psi_T \sin \lambda_T \quad \text{(AI-2)}$$

$$z = x_1 \sin \psi_T + z_1 \cos \psi_T$$

A body-fixed coordinate system x_2, y_2, z_2 is defined such that the x_2 axis lies along the vehicle axis from its base toward its nose. The z_2 axis is set arbitrarily to some direction consistent with the value of the material orientation angle used. Vehicle orientation with respect to the local coordinate system is given by two angles θ_T and ϕ_T. Transformation is accomplished (see Fig. 16b) by first rotating the x_1, y_1, z_1 system about the y_1 axis (counterclockwise when looking along y_1) an amount ϕ_T so that z_1 moves to z_2. This system is then rotated about the z_2 axis (clockwise when looking along z_2) an amount θ_T so that x_1 and y_1 move to x_2 and y_2 respectively. This transformation may be expressed by the following equations, where x_2, y_2, z_2 are components of any vector in the body-fixed system and x_1, y_1, z_1 are components of the same vector in the local system:

$$x_1 = x_2 \cos \theta_T \cos \phi_T - y_2 \sin \theta_T \cos \phi_T + z_2 \sin \phi_T$$

$$y_1 = x_2 \sin \theta_T + y_2 \cos \theta_T \quad \text{(AI-3)}$$

$$z_1 = -x_2 \cos \theta_T \sin \phi_T + y_2 \sin \theta_T \sin \phi_T + z_2 \cos \phi_T$$

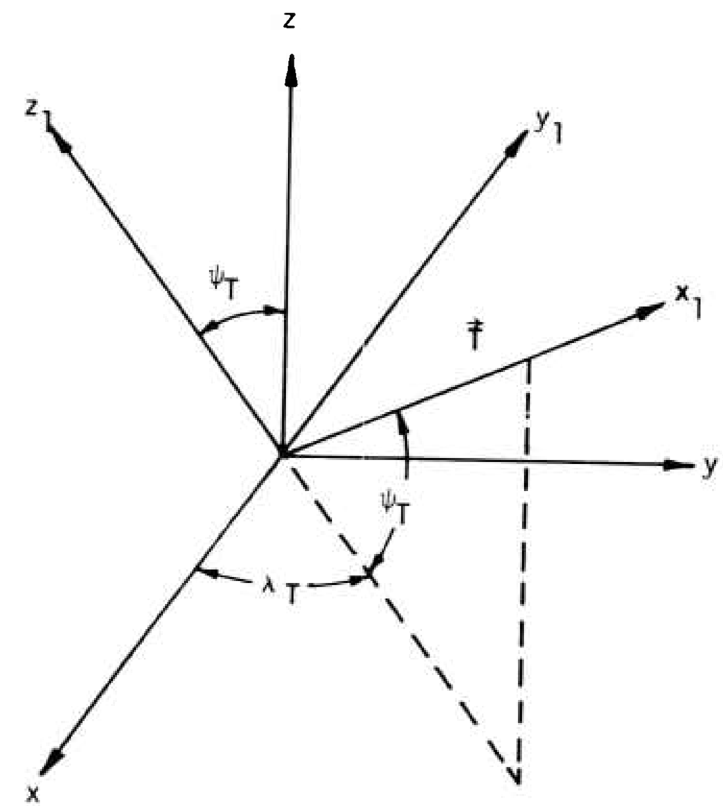


Figure 16a. Earth-Fixed to Local Coordinate Transformation

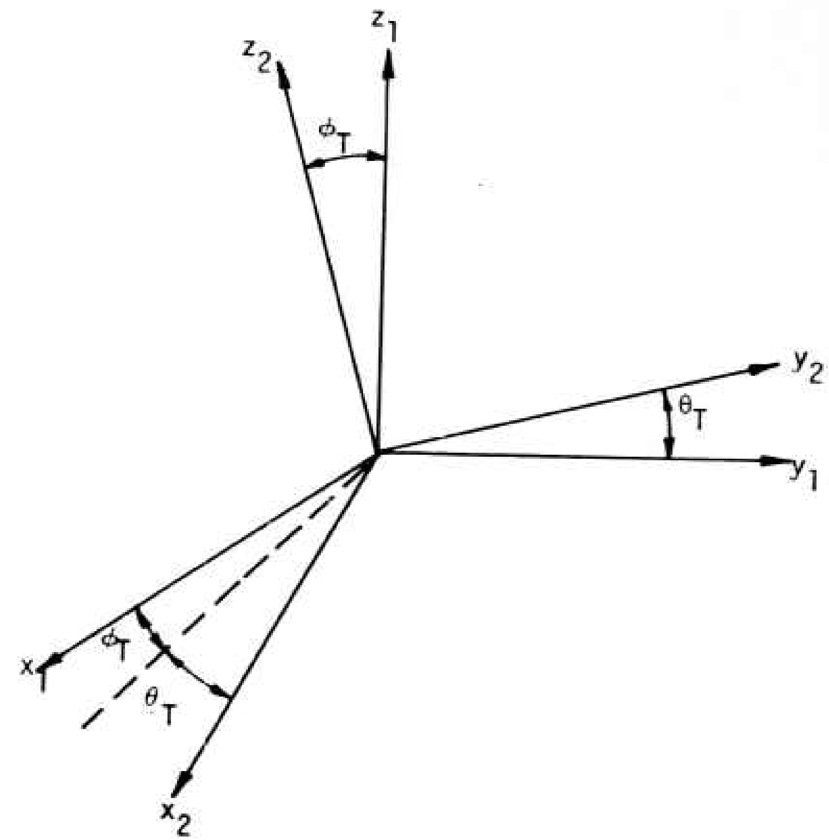


Figure 16b. Local Body-Fixed Coordinate Transformation

Combining Eqs. AI-2 and AI-3, it is possible to express the components x, y, z in terms of x_2, y_2, z_2:

$$x = x_2(\cos\theta_T \cos\phi_T \cos\psi_T \cos\lambda_T - \sin\theta_T \sin\lambda_T$$

$$+ \cos\theta \sin\phi \sin\psi \cos\lambda) - y_2(\sin\theta_T \cos\phi_T \cos\psi_T$$

$$\cos\lambda_T + \cos\theta_T \sin\lambda_T + \sin\theta_T \sin\phi_T \sin\psi_T \cos\lambda_T)$$

$$+ z_2(\sin\phi_T \cos\psi_T \cos\lambda_T - \cos\phi_T \sin\psi_T \cos\lambda_T) \quad \text{(AI-4a)}$$

$$y = x_2(\cos\theta_T \cos\phi_T \cos\psi_T \sin\lambda_T + \sin\theta_T \cos\lambda_T$$

$$+ \cos\theta_T \sin\phi_T \sin\psi_T \sin\lambda_T) + y_2(\cos\theta_T \cos\lambda$$

$$- \sin\theta_T \cos\phi_T \cos\psi_T \sin\lambda_T - \sin\theta_T \sin\phi_T \sin\psi_T$$

$$\sin\lambda_T) + z_2(\sin\phi_T \cos\psi_T \sin\lambda_T - \cos\phi_T \sin\psi_T \sin\lambda_T \quad \text{(AI-4b)}$$

$$z = x_2(\cos\theta_T \cos\phi_T \sin\psi_T - \cos\theta_T \sin\phi_T \cos\psi_T)$$

$$+ y_2(\sin\theta_T \sin\phi_T \cos\psi_T - \sin\theta_T \cos\phi_T \sin\psi_T)$$

$$+ z_2(\sin\phi_T \sin\psi_T + \cos\phi_T \cos\psi_T) \quad \text{AI-4c)}$$

Elemental areas on the targets are defined (see Fig. 17) by subdividing the spherical portion angularly in two directions, ϕ_s and θ_s, the cone angularly in one direction, θ_c, and the base as one element. Components of these vectors in the body-fixed coordinate system are given by:

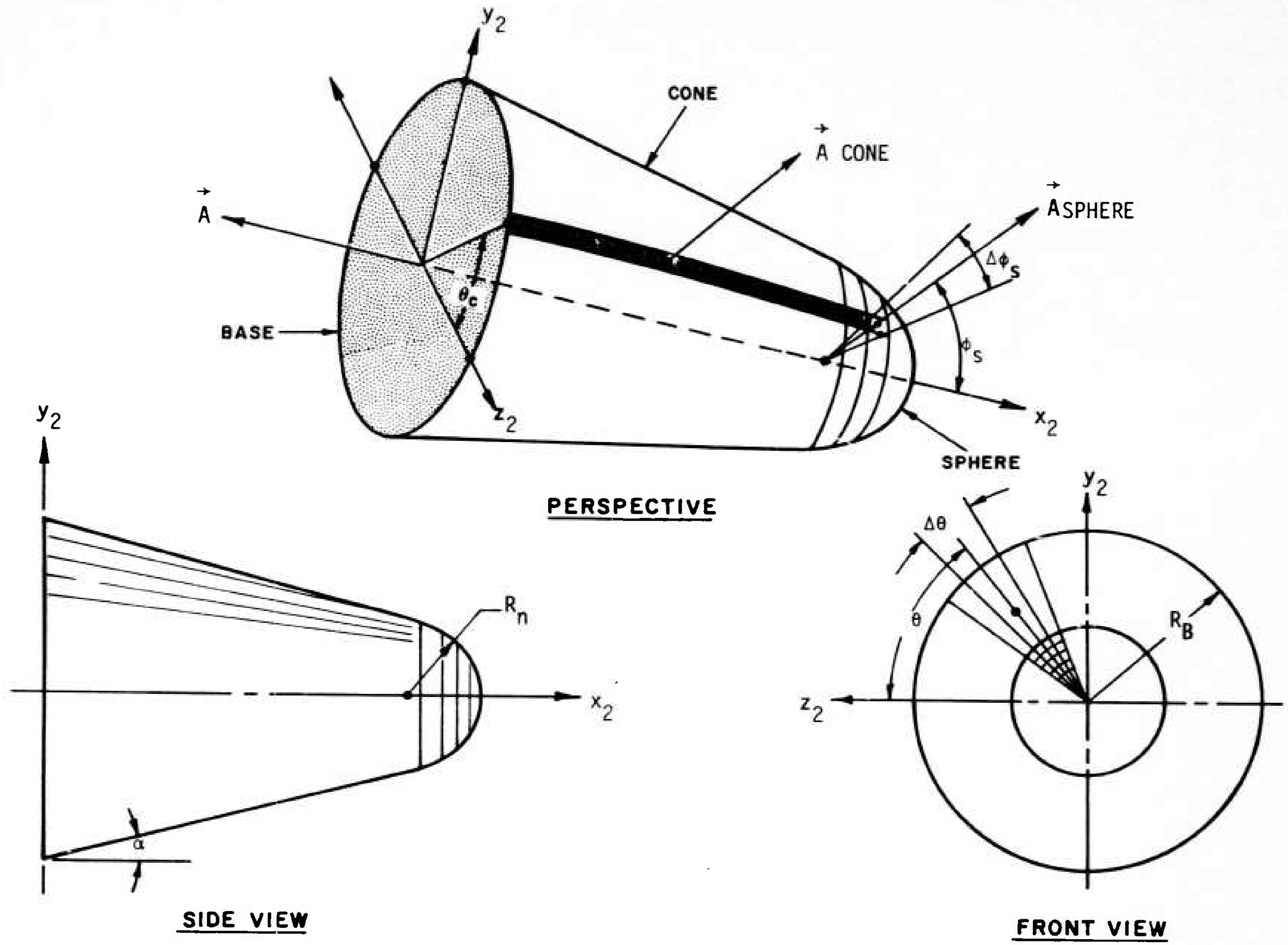


Figure 17. Target Geometry

$$A_{b_x} = -A_b \qquad A_{b_y} = 0 \qquad A_{b_z} = 0 \tag{AI-5}$$

$$A_{c_x} = A_c \sin\alpha \qquad A_{c_y} = A_c \cos\alpha \sin\theta_c \qquad A_{c_z} = A_c \cos\alpha \cos\theta_c \tag{AI-6}$$

$$A_{s_x} = A_s \cos\phi_s \qquad A_{s_y} = A_s \sin\phi_s \sin\theta_s \qquad A_{s_z} = A_s \sin\phi_s \cos\theta_s \tag{AI-7}$$

where $\qquad A_b = \pi R_b^2$

$$A_s = \Delta\theta_s \Delta\phi_s R_n^2 \sin\phi_s \tag{AI-8}$$

$$A_c = \frac{\Delta\theta_c}{2\sin\alpha}\left(R_b^2 - R_n^2\cos^2\alpha\right)$$

or if $\alpha = 0$, $A_c = \Delta\theta_c R_n L$, where α is the cone half angle, R_n is the nose radius, R_b is the base radius, and L is the cylinder length. An integer number of angular elements are specified (N_{ϕ_s}, N_{θ_s}, N_{ϕ_s}) so that:

$$\Delta\theta_c = \frac{2\pi}{N_{\theta_c}} \qquad \Delta\theta_s = \frac{2\pi}{N_{\theta_s}} \qquad \Delta\phi_s = \left(\frac{\pi}{2} - \alpha\right)/N_{\phi_s} \tag{AI-9}$$

As a check on the program, the total projected area of the target may be calculated given the observer unit position vector components V_x, V_y, V_z in the earth-fixed system. This vector is dotted with each area normal vector to give the projected area that each element presents to the viewer:

$$\begin{aligned} A_p &= A\cos\gamma = \vec{A}\cdot\hat{V} \\ &= A_x V_x + A_y V_y + A_z V_z \end{aligned} \tag{AI-10}$$

If the dot product is negative, indicating the area if facing away from the viewer, the element is not considered. All the other contributions are summed to give the total projected area of the target.

C. INPUT/OUTPUT SPECIFICATIONS

Table 7 defines the input necessary to use this code. The first data card must contain the letters TAR to indicate the operator desires to use this code. All codes except SURAD require the output generated by TARG.

Special target shapes may be handled by proper selection of R_n, R_b, L and α. A pure cone is specified by setting R_n to zero, a hemisphere by setting α and L to zero, a hemisphere-cylinder by setting α to zero and simple circular flat plate (one sided) by setting R_n, α, and L to zero. If R_n is set to zero, N_{ϕ_s} and N_{θ_s} should also be set to zero, and similarly for N_{θ_c} if XL is zero.

Results (the X-array) are written on a disc file labeled TAPE4 for use in latter programs. Aside from intermediate output generated by TARG for debug purposes when W equals "1." or "2.", no output is generated for the printer.

*X(I) X(j + 1), X(j + 2), X(j + 3) = A_x, A_y, A_z

X(k + 1), X(k + 2), X(k + 3) = M_x, M_y, M_z

where

j = 1, 2, ..., N
k = N + 1, N + 2, N + 3 ..., 2N
N = NPS · NTS + NTC + 1

*OUTPUT

TABLE 7
INPUT DATA FOR TARG

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
TLAT	ψ_T, target latitude	degrees	-90. to 90.	0.	$-90. \leq TLAT \leq 90.$
TLON	λ_T, target longitude	degrees	0. to 360.	0.	$0. \leq TLON \leq 360.$
PT	ϕ_T, target orientation angle	degrees	N.A.	0.	N.A.
TT	θ_T, target orientation angle	degrees	N.A.	0.	N.A.
RN	Nose radius	cm	$RN \geq 0.$	1.	1.
RB	R_b, base radius (if $\alpha \neq 0$)	cm	$RB \geq 0.$	2.	2.
XL	L, cylinder length (if $\alpha = 0$)	cm	$XL \geq 0.$	0.	0.
A	α, cone half angle	degrees	$-90. \leq A < 90.$	30.	0.-45.

TABLE 7 (Cont.)

INPUT DATA FOR TARG

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
NPS	N_{ϕ_s}, number of elements in ϕ_s direction	dimen-sionless	NPS $\geq$ 0*	15	NPS = $\frac{1}{2}$ NTS
NTC	N_{θ_c}, number of elements in θ_c direction	dimen-sionless	NTS $\geq$ 0*, 6[(NPS) (NTS) + NTC +1] $\leq$ 14,000	40	40
NTS	N_{θ_s}, number of elements in θ_s direction	dimen-sionless	NTC $\geq$ 0 (= 0 if XL = 0)	40	40
VX	x component of unit position vector toward viewer; if > 1 projected area calculation is eliminated	dimen-sionless	unless VX > 1: $VX^2 + VY^2 + VZ^2 = 1.0$	2.	2.
VY	y component of unit position vector toward viewer	dimen-sionless	$-1 \leq VY \leq 1$	0.	0.

*Both NPS and NTS equal zero if RN = 0.

TABLE 7 (Cont.)

INPUT DATA FOR TARG

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
VZ	z component of unit position vector toward viewer	dimensionless	$-1. \leq VZ \leq 1.$	0.	0.
W	Control parameter: 0 - no write, 1 writes only preliminary results, 2 writes preliminary and final results	dimensionless	0. or 1. or 2.	0.	0.

APPENDIX II
EARTH-ELEMENT CODE (EARTH)

A. INTRODUCTION

This digital computer code is one of a series designed to calculate the radiant intensity of exoatmospheric objects. The specific purpose of this code is to: (1) subdivide the portion of the earth which irradiates a given target location into a specified number of elemental areas, (2) calculate the components of the unit vectors pointing toward this target position from each elemental area on the earth, and (3) calculate the irradiance at the target location due to both earth-emitted radiance and earth-reflected sunlight given the position of the sun. These results are used in subsequent computer codes, DIFUS1 and TINTF.

B. DEVELOPMENT OF EQUATIONS

Components of the vectors are found in an earth-fixed coordinate system (x, y, z) defined (see Fig. 15) by the origin at the center of the earth, the z-axis pointing north and the x-axis toward the Greenwich Meridian (all coordinate systems herein are right-handed Cartesian). The target location vector $\vec{T}$ in this earth-fixed coordinate system can be given in terms of the target's longitude, λ_T, its latitude, ψ_T (positive in the Northern Hemisphere, negative in the Southern Hemisphere), and its altitude β (normalized to the earth's radius), by:

$$\vec{T} = \hat{i}\beta \cos \psi_T \cos \lambda_T - \hat{j}\beta \cos \psi_T \sin \lambda_T + \hat{k}\beta \sin \psi_T \qquad \text{(AII-1)}$$

where $\hat{i}$, $\hat{j}$, and $\hat{k}$ are unit vectors along the x, y, and z axes respectively. Using the sun's longitude λ_s and latitude ψ_s, the unit vector toward the sun is similarly:

$$\hat{s} = \hat{i} \cos \psi_s \cos \lambda_s - \hat{j} \cos \psi_s \sin \lambda_s + \hat{k} \sin \psi_s \qquad \text{(AII-2)}$$

For convenience a local coordinate system (x_1, y_1, z_1) is set up with the origin again at the center of the earth, the z_1 axis pointing toward the target and the z axis in the x_1-z_1 plane. This transformation may be expressed by the following equations, where x_1, y_1, z_1 are components of any vector in the local coordinate system and x, y, z are components of the same vector in the earth-fixed system:

$$x = x_1 \sin \psi_T \cos \lambda_T + y_1 \sin \lambda_T + z_1 \cos \psi_T \cos \lambda_T$$

$$y = -x_1 \sin \psi_T \sin \lambda_T + y_1 \cos \lambda_T - z_1 \cos \psi_T \sin \lambda_T \qquad \text{(AII-3)}$$

$$z = -x_1 \cos \psi_T + z_1 \sin \psi_T$$

Assuming a spherical earth, the portion which irradiates the target (see Fig. 18) is:

$$\cos \phi_m = 1/\beta \qquad \text{(AII-4)}$$

This earth disk is subdivided into n_ϕ elemental angles in the ϕ direction and n_θ in the θ direction, so that the sizes of the elements are

$$\Delta\phi = \phi_m/n_\phi$$

$$\Delta\theta = 2\pi/n_\theta \qquad \text{(AII-5)}$$

$$\Delta A = \Delta\phi\Delta\theta \sin \phi \quad .$$

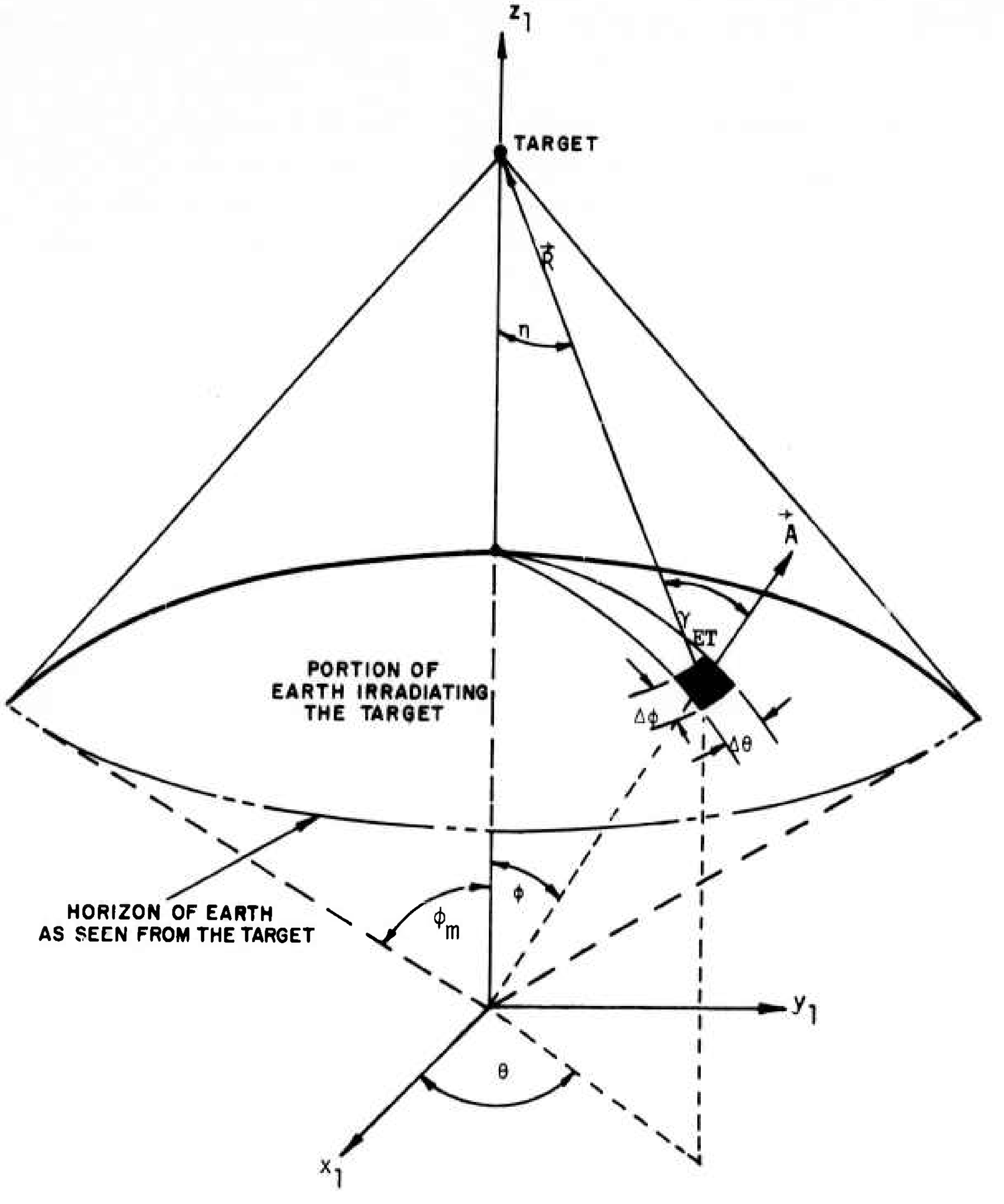


Figure 18. Earth-Target Geometry

The area normal vector $\vec{A}$, having a magnitude equal to the size of the element and a direction normal to it, may be expressed in the local coordinate system by:

$$\vec{A} = (\hat{i} \sin\phi \cos\theta + \hat{j} \sin\phi \sin\theta + \hat{k} \cos\phi)\ \Delta\phi\Delta\theta \sin\phi \quad \text{(AII-6)}$$

The position of each of the elemental areas is given by a unit vector E, expressed in the local system by:

$$\hat{E} = \hat{i} \sin\phi \cos\theta + \hat{j} \sin\phi \sin\theta + \hat{k} \cos\phi \quad \text{(AII-7)}$$

Both these vectors are transformed to the earth-fixed coordinate system using Eq. AII-3. By vectorially subtracting E from T we get the range vector R from the area element to the target:

$$\vec{R} = \vec{T} - \hat{E} \quad \text{(AII-8)}$$

Assuming the elemental areas radiate diffusely, the irradiance at the target due to any one of them is:

$$E_E = (NA/R^2) \cos\gamma_{ET} \quad \text{(AII-9)}$$

where N is the radiance of the earth element, γ_{ET} is the angle between $\vec{A}$ and $\vec{R}$. Spectral earth radiance at any wavelength is assumed dependent only on the local nadir angle "η" (see Fig. 19), which can be expressed as:

$$\eta = \tan^{-1} \frac{\sin\phi}{\beta - \cos\phi} \quad \text{(AII-10)}$$

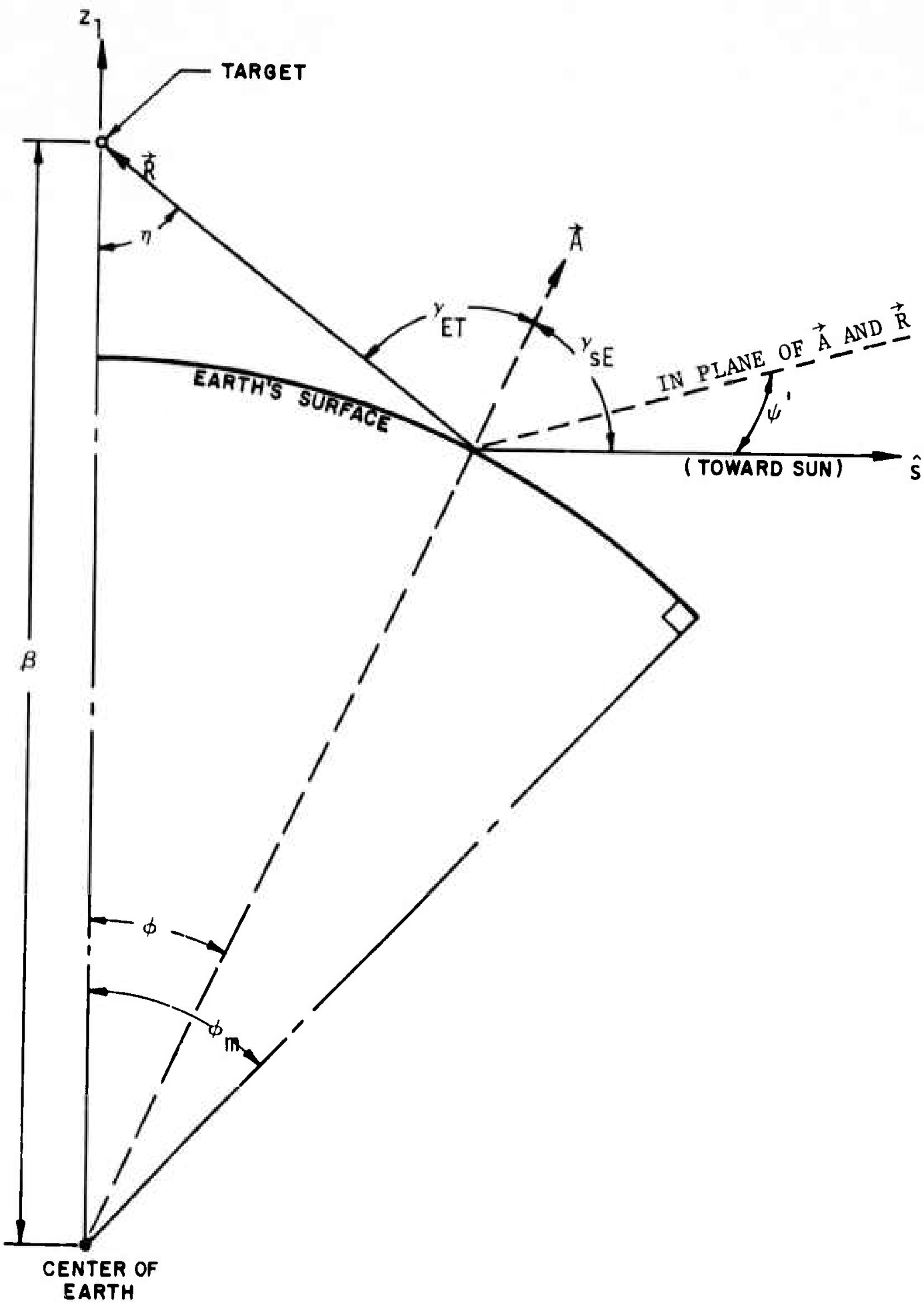


Figure 19. Sun-Earth-Target Geometry

The other quantities are:

$$\gamma_{ET} = \phi + \eta \quad \text{and} \quad R = \frac{\sin \phi}{\sin \eta} \qquad \text{(AII-11)}$$

Irradiance at the target due to earth-reflected sunlight can be expressed as:

$$E_s = \frac{\rho G_s A}{R^2} \cos \gamma_{sE} \cos \gamma_{ET} \qquad \text{(AII-12)}$$

where ρ is the local value of albedo (bidirectional reflectance) and G_s is the solar irradiation. A subroutine "ALBEDO" performs a table look-up operation using linear interpolation given the values ψ_T, γ_{sE}, γ_{ET} and ψ. Using vector algebra:

$$\cos \gamma_{sE} = \hat{A} \cdot \hat{S} \qquad \text{(AII-13)}$$

$$\cos \psi' = \hat{M} \cdot \hat{N} \qquad \text{(AII-14)}$$

where $\psi = \pi - \psi'$ and

$$\vec{M} = \hat{s} \times \vec{A} \quad \text{and} \quad \vec{N} = \vec{A} \times \vec{R} \qquad \text{(AII-15)}$$

An option is included as a check on the code to calculate the total view factor between the target and the portion of the earth irradiating it, for emitted earthshine F_e and for reflected sunlight F_s.

C. INPUT/OUTPUT SPECIFICATIONS

Tables 8 and 9 define the input necessary to use this code. Table 9 is needed only if earth-reflected sunlight is to be considered.

The first data card provided after the TARG input data must contain the letters EAR to indicate the operator desires to use this code. Only codes TINTF and DIFUS1 require the output from EARTH.

Output is written in three sets. The first and second write the x, y, and z components of the R vector, E_E and E_s for each earth element. However, to save storage and writing time, if the sun does not irradiate an element, the sign of E_E is reversed and no value of E_s is written. The first set is written in binary on a disc file labeled TAPE10 for use in subsequent computer codes TINTF and DIFUS1, and the second (if WRITE is set equal to one) is printed out for debug purposes. In these outputs, the x, y, and z components (in that order) of all the earth elements are written first in the same order in which they were calculated; that is, all the θ's in the first ϕ ring, then all the θ's in the second ϕ ring, and so on, until all the ϕ rings are written. After the components of the R's, the values of E_E and E_s are written in the same order as above. First the E_E then the E_s for each earth element (unless E_E is negative, in which case E_s is not given). The third set, the "point view factors" which the total and the sunlit portions of the earth present to the target, are printed out if CK is set equal to one.

TABLE 8

INPUT DATA FOR EARTH

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
TALT	β, target radius/radius of earth	dimen-sionless	>1.	1.125	1.125
TAD	ψ_T, target latitude	degrees	$-90. \leq \psi_T \leq 90.$	0.	0.
TOD	λ_T, target longitude	degrees	$0. \leq \lambda_T \leq 360.$	0.	0.
SAD	ψ_s, sun latitude	degrees	$-90. \leq \psi_s \leq 90.$	0.	0.
SOD	λ_s, sun longitude	degrees	$0. \leq \lambda_s \leq 360.$	0.	0.
NPE	N_ϕ, number of earth elements, polar	dimen-sionless	>0	15	15
NTE	N_θ, number of earth elements, azimuthal	dimen-sionless	>0	40	40

TABLE 8 (Cont.)

INPUT DATA FOR EARTH

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
T9	$N_E(\eta)$ angular distribution of earth radiance every ten degrees: 0, 10, ...90	W/cm^2-sr	N.A.	1.	1.
G	G_s, solar irradiance	W/cm^2	N.A.	.14	.14
NEW	Control parameter. If=1 albedo data is to be read. If≠1 ≠ if not first of sequential calculation.	dimensionless	N.A.	0	0
WRITE	Control parameter. If = 1, write X's in numeric symbols for debug purposes. If = 0, no intermediate results are printed.	dimensionless	N.A.	0.	0.
NT2	Number of entries in R/S vs. ψ_T albedo table	dimensionless	≥ 2	23	23
NT3	Number of entries in $\frac{r(\xi) \cos \xi}{r(0)}$ vs. ξ albedo table	dimensionless	≥ 2	23	22

TABLE 8 (Cont.)

INPUT DATA FOR EARTH

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
NT5	Number of θ's in $\frac{r(^{\xi}0)}{\rho(\theta,\ \psi,\ \xi_0)}$ albedo table	dimen- sionless	≥ 2	10	10
NT7	Number of ψ's in $\frac{r(^{\xi}0)}{\rho(\phi,\ \psi,\ \xi_0)}$ albedo table	dimen- sionless	≥ 2	13	13
CK	Control parameter. If = 1, calculates and writes view factors. If = 0, no view factors are calculated or printed.	dimen- sionless	1. or 0.	1.	1.

TABLE 9

ALBEDO TABLE INPUTS

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
T1	R/S entries	dimen-sionless	$0. \leq R/S \leq 1.$	N.A.	$.20 \leq R/S \leq .82$
T2	ψ entries for R/S table	radians	$-\pi/2 \leq \psi \leq \pi/2$	N.A.	$-\pi/2 \leq \psi \leq \pi/2$
T3	$\frac{r(\xi)}{r(0)}$	dimen-sionless	$0. \leq \frac{r(\xi)}{r(0)} \leq 1$	N.A.	$0. \leq \frac{r(\xi)}{r(0)} \leq 1.$
T4	ξ entries for $\frac{r(\xi)}{r(0)}$ table	radians	$0. \leq \xi \leq \pi/2$	N.A.	$0. \leq \xi \leq \pi/2$
T5	θ entries for $\frac{r(\xi_0)}{\rho(\theta,\ \psi,\ \xi_0)}$ table	radians	$0. \leq \theta \leq \pi/2$	N.A.	$0. \leq \theta \leq \pi/2$
T6	$\frac{r(\xi)}{\rho(\theta,\ \psi,\ \xi_0)}$ Entries	sr^{-1}	$\frac{r(\xi)}{\rho(\theta,\ \psi,\ \xi_0)} \geq 0.$	N.A.	$0.2 \leq \frac{r(\xi)}{\rho(\theta,\ \psi,\ \xi_0)} \leq 1.52$

TABLE 9 (Cont.)

ALBEDO TABLE INPUTS

FORTRAN Symbol	Definition	Units	Range of Allowable Values	Value Used if Not Set	Typical Values
T7	ψ entries for $\frac{r(\xi)}{\rho(\theta, \psi, \xi_0)}$ table	radians	$0. \leq \psi \leq \pi$	N.A.	$0. \leq \psi \leq \pi$
T8	ξ entries for $\frac{r(\xi)}{\rho(\theta, \psi, \xi_0)}$ Table	radians	$0. \leq \xi \leq \pi/2$	N.A.	$0. \leq \xi \leq \pi/2$

APPENDIX III
EMITTED RADIATION CODE (HRAD)

A. INTRODUCTION

This code is designed to calculate the radiant emission of a target given to temperature and emissivity. The radiation emitted by a reentry vehicle is a function of its surface temperature and spectral emissivity. For the purpose of numerical calculation, the surface is divided into "n" sections which are sufficiently small to be assumed isothermal. For a Lambertian radiator, the radiant intensity is

$$I_\lambda = \frac{C_1}{\pi} \sum_{0}^{n=N} A_n \, \varepsilon(\lambda, T_n) \lambda^{-5} \left[e^{(C_2/\lambda T_n)} - 1 \right]^{-1}$$

where
- A is the projected area (cm^2)
- $I_{\Delta\lambda}$ is the radiant intensity ($W\text{-}sr^{-1}$)
- $\varepsilon(\lambda, T)$ is the spectral emissivity
- λ is the wavelength (μm)
- T is the surface temperature (°R)
- $C_1 = 3.7413 \times 10^4 \; W/cm^2\text{-}\mu m^4$
- $C_2 = 2.59 \times 10^4 \; \mu m\text{-}°R$

The radiant intensity is obtained by integrating over wavelength:

$$I_{\Delta\lambda} = \frac{C_1}{\pi} \sum_{0}^{n=N} A_n \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda, T_n) \lambda^{-5} \left[e^{(C_2/\lambda T_n)} - 1 \right]^{-1} d\lambda$$

A series approximation to this integral of Planck's equation that is used in the program follows:

$$I_{\Delta\lambda} = \sum_{0}^{n=N} \frac{C_1 T_n^4 \varepsilon(\lambda, T_n) A_n}{C_2^4} \left[\sum_{k=1}^{\infty} e^{-kX_2} \left(\frac{X_2^3}{k} + \frac{3X_2^3}{k^2} + \frac{6X_2}{k^3} + \frac{6}{k^4} \right) \right.$$

$$\left. - \sum_{k=1}^{\infty} e^{-kX_1} \left(\frac{X_1^3}{k} + \frac{3X_1^2}{k^2} + \frac{6X_1}{k^3} + \frac{6}{k^4} \right) \right]$$

where $X_1 = C_2/\lambda_1 T_n$

$X_2 = C_2/\lambda_2 T_n$

The HRAD program calculates the radiance and radiant intensity, spectral and/or integrated, for the surface in question, given: (1) temperature, emissivity, and size of isothermal areas; (2) spectral wavelengths; and (3) limits of integration.

The assumptions incorporated in the program are:

1. Multiple-isothermal-area concept
2. Lambertian radiator
3. Emissivity a function of area and wavelength

The latter assumption does not reflect the difficulty inherent in the inclusion of variable emissivity but rather a lack of information on the spectral and thermal behavior of optical properties of current reentry vehicle heat shield materials.

B. COMPUTER CODE

```
THE HRAD PROGRAM CALCULATES THE RADIANCE AND RADIANT INTENSITY,
SPECTRAL AND/OR INTEGRATED, FOR THE SURFACE IN QUESTION, GIVEN
   1.  TEMPERATURE, EMISSIVITY, AND SIZE OF ISOTHERMAL AREAS
   2.  SPECTRAL WAVELENGTHS
   3.  LIMITS OF INTEGRATION
THE ASSUMPTIONS INCORPORATED IN THE PROGRAM ARE
   1.  MULTIPLE-ISOTHERMAL-AREA CONCEPT
   2.  LAMBERTIAN RADIATOR
   3.  EMISSIVITY A FUNCTION OF AREA AND INTEGRATION WAVELENGTH


INPUT SETUP
CARD 1 - IDENTIFICATION TO BE PRINTED ON THE RUN (FORMAT16A5)

CARD 2 - NASPEC, NAREAS, NTIMES, NLAMBS, NDLAMS (FORMAT 5I10)

NASPEC - NUMBER OF ASPECTS
NAREAS - NUMBER OF AREAS
NTIMES - NUMBER OF TIMES
NLAMBS - NUMBER OF SPECTRAL WAVELENGTHS
NDLAMS - NUMBER OF INTEGRATED WAVELENGTH BANDS

CARD SET 3        (ASPEC(I),I=1,NASPEC)          FORMAT (8F10.6)

ASPEC      - THE VALUES OF THE ASPECT ANGLES

CARD SET 4 - DESCRIPTION OF AREAS.  THE INFORMATION WILL VARY
             ACCORDING TO THE TYPE OF SURFACE WITHIN EACH SECTION
NTYPE    THE TYPE CLASSIFIED

NTYPE=1  SPHERICAL CAP
INPUT IS  NTYPE, RAD, ANGLE,  FORMAT (I5,2F10.3)
RAD      - CAP RADIUS
ANGLE    - THE ANGLE FROM THE CENTER OF THE HEMISPHERE TO THE EDGE
           OF THE CAP.  IF THE CAP IS A HEMISPHERE, ANGLE=0

NTYPE =2  CYLINDER
INPUT IS NTYPE, RAD, LENGTH     FORMAT (I5,2F10.3)
RAD      - THE CYLINDER RADIUS
LENGTH   - THE LENGTH OF THE CYLINDER
```

```
NTYPE =3 OR 4    CONE OR CONIC FUNCTION
INPUT IS
1.  NTYPE,REAR RADIUS OF VEHICLE, NO. OF CONES, CONE ANGLE
  FORMAT (I5,3F10.3)
2.  XLEN(1-NO. OF CONES)          FORMAT (8F10.6)
XLEN  -  THE LENGTHS FOR EACH CONE FRUSTRUM

NTYPE =5  FLAT PLATE
INPUT IS NTYPE, RAD, ANGLE FORMAT (I5,2F10.3)
 RAD   - THE RADIUS OF THE PLATE
ANGLE    - THE ANGLE BETWEEN THE PLATE NORMAL AND THE AXIS OF
           SYMMETRY.  USUALLY WILL BE EITHER 0 OR 180 DEGREES

NTYPE =6    REAR SPHERICAL PLATE    FOR INPUT SEE NTYPE=1


CARD SET 5 - EMISS(NDLAMS,NAREAS)     (FORMAT 8F10.6)
EMITTANCE FOR EACH AREA AND FOR EACH INTEGRATED WAVELENGTH.
EACH CARD REPRESENTS EMITTANCE VALUES FOR A WAVELENGTH BAND

CARD SET 6   - XLAM1, XLAM2, XINC
XLAM1 = LOWER LIMIT OF THE WAVELENGTH FOR THE SPECTRAL CALCULATION
XLAM2 = UPPER LIMIT OF THE WAVELENGTH FOR THE SPECTRAL CALCULATION
XINC  = INCREMENT SPECIFICATION FOR THE WAVELENGTH

CARD SET 7   -   LAMBD1(NDLAMS), LAMBD2(NDLAMS)    (FORMAT 3F10.6)
INTEGRATED RADIATION LIMITS.  INPUT ALL LOWER THAN ALL UPPER
VALUES.  THERE WILL BE NDLAMS VALUES FOR EACH.

CARD SET 8 - TEMPER(NAREAS)    (FORMAT 8F10.6)
TEMPERATURE FOR EACH AREA.  INPUT WOULD CONSIST OF NTIME CARDS
WITH NAREAS VALUES PER CARD.

CARD SET 9 -   (FORMAT I5)
BLANK CARD WILL END INPUT.  A VALUE TO CONTINUE READING.
```

APPENDIX IV

STANDARD INPUT DATA TO SURAD CODE

LD*

```
-6.041966 -6.344979 -6.670900 -7.023516 -7.440010 -7.918565 -8.396698 -8.879584
-9.364537 -9.842448-10.313526-10.787342-11.258243-11.712508-12.151224-12.575472
-12.973052-13.351738-13.714945-14.081374-14.455971-14.822995-15.202755-15.602361
-16.023653-16.470040-16.943497-17.488168-18.050008-18.611019-19.191701-19.774055
-20.328761-20.863692-21.389028-21.879405-22.340385-22.815336-23.247141-23.638910
-24.042622
```

END3,END4

```
12  9  6  4  1  1  1  1  1  2  2  3  3  4  4  4  5  5  6  6  7  7  7  7
 8  8  9  9 10 10 11 11 12 12 13 13 14 14 15 15 15 16 16 16 13 14 15 16
17 18 18 19 20 20 21 22 23 24 25 26 27 27 28 29 30 31 32 32 33 34 34 36
36 36 36 36 36 36 36 36 36 36 36 36 36 36 29 29
```

LM, FPP, TM, TB, R, PO, MINT42, EPSI42, C1, C2

```
5.4   0.0  -7.2  -3.6   0.0
 5.04  1.8   0.0 -11.7 90.79.61.52.47.32.20.11. 0. 325.17 325.17 454.77 487.17
487.17 411.57 389.97 389.97 518.67 3240.0  1716.54 2117.0
4.0 0.2 .68E-02 .37E-06
```

*Headings are provided for clarification and are not to be punched data.

```
END1,END2, RHOO, MUO, RETRAN, HB, LE, PR, TO

 5  5  5  4  4  3  3  3  2  2  2  1  2  3  4  5  6  8  9 11 12 13 14 15
16 17 19 20 21 22 23 25 26 28 28 28 10 12 14 17 19 21 25 27 29 31 33 35
37 39 42 44 44 44 44 44 44 44 44 44 44 44 44 44 43 43 43 43 43 43 43 43
.2498E-02    .36E-06      .5E06
  25.9       1.4      0.72   491.7

IKL, GL, ERROR, ERORT
5 25      1.0        10.0

TEMPER
      .0      .0      .0      .0  3906.0  3744.0  3348.0  3006.0  2646.0  2448.0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .0      .0      .0      .0  5022.0  4590.0  4194.0  3798.0  3438.0  3060.0
  2718.0  2304.0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .0      .0      .0      .0  6102.0  5598.0  5130.0  4644.0  4284.0  3852.0
  3510.0  3150.0  2754.0  2448.0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .0      .0      .0  7866.0  7200.0  6660.0  6120.0  5598.0  5184.0  4734.0
  4302.0  3906.0  3492.0  3168.0  2844.0  2412.0  2124.0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .0      .0      .0  9090.0  8424.0  7776.0  7182.0  6624.0  6174.0  5634.0
  5220.0  4806.0  4374.0  3960.0  3600.0  3222.0  2970.0  2556.0  2304.0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
```

TEMPTER (Cont'd)

```
      .0        .0        .0        .0
      .0        .011304.010440.0 9684.0 8964.0 8280.0 7686.0 7164.0 6624.0
 6120.0 5724.0 5202.0 4860.0 4446.0 3996.0 3708.0 3312.0 2916.0 2664.0
 2304.0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .0      .012798.011880.010944.010134.0 9396.0 8730.0 8082.0 7560.0
 7020.0 6570.0 6156.0 5706.0 5274.0 4860.0 4482.0 4104.0 3744.0 3384.0
 2988.0 2592.0 2286.0 2034.0 1746.0      .0      .0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .0      .014400.013320.012312.011376.010548.0 9828.0 9108.0 8460.0
 7884.0 7362.0 6894.0 6444.0 6048.0 5706.0 5256.0 4950.0 4500.0 4140.0
 3780.0 3420.0 3042.0 2718.0 2358.0 2034.0 1692.0      .0      .0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .016992.015858.014796.013752.012744.011826.010944.010134.0 9324.0
 8712.0 8136.0 7614.0 7164.0 6750.0 6354.0 5940.0 5616.0 5220.0 4896.0
 4590.0 4176.0 3852.0 3510.0 3150.0 2790.0 2358.0 1980.0 1782.0      .0
      .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .018396.017118.016092.014994.014040.013140.012204.011340.010494.0
 9702.0 9018.0 8424.0 7848.0 7380.0 6948.0 6534.0 6174.0 5850.0 5544.0
 5220.0 4896.0 4590.0 4266.0 3906.0 3546.0 3168.0 2790.0 2466.0 2178.0
 1746.0      .0      .0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
      .019530.018342.017226.016164.015210.014238.013374.012510.011646.0
10818.010080.0 9360.0 8658.0 8064.0 7560.0 7146.0 6714.0 6354.0 6030.0
 5706.0 5418.0 5148.0 4860.0 4554.0 4248.0 3924.0 3564.0 3222.0 2934.0
 2592.0 2268.0 1944.0      .0      .0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
21906.020610.019404.018216.017082.016182.015264.014364.013536.012690.0
11880.011124.010422.0 9684.0 8910.0 8280.0 7740.0 7236.0 6840.0 6462.0
 6120.0 5832.0 5526.0 5256.0 5022.0 4770.0 4482.0 4212.0 3960.0 3672.0
 3330.0 2970.0 2610.0 2232.0 1854.0      .0      .0      .0      .0      .0
      .0      .0      .0      .0
```

TEMPER (Cont'd)

```
23076.021690.020394.019170.018090.017064.016164.015228.014436.013662.0
12834.012096.011394.010710.0 9954.0 9234.0 8586.0 7956.0 7416.0 6984.0
 6606.0 6264.0 5940.0 5634.0 5364.0 5130.0 4914.0 4716.0 4464.0 4212.0
 3978.0 3672.0 3366.0 3006.0 2646.0 2286.0 1998.0     .0     .0     .0
     .0     .0     .0     .0
     .022482.021312.020106.018900.017838.016902.015984.015156.014382.0
13680.012924.012276.011574.010926.010296.0 9576.0 8910.0 8262.0 7650.0
 7074.0 6678.0 6282.0 5958.0 5688.0 5454.0 5238.0 5022.0 4806.0 4572.0
 4374.0 4140.0 3870.0 3654.0 3384.0 3024.0 2718.0 2340.0 1926.0     .0
     .0     .0     .0     .0
     .0     .022212.020952.019728.018648.017640.016650.015840.015048.0
14346.013626.012942.012276.011646.011034.010458.0 9864.0 9270.0 8604.0
 7956.0 7398.0 6876.0 6462.0 6102.0 5814.0 5544.0 5310.0 5094.0 4896.0
 4716.0 4500.0 4320.0 4104.0 3888.0 3672.0 3420.0 3114.0 2754.0 2358.0
 2016.0 1728.0     .0     .0
     .0     .0     .021816.020556.019566.018324.017316.016470.015624.0
14850.014166.013464.012816.012240.011664.011124.010584.0 9990.0 9486.0
 8892.0 8316.0 7686.0 7092.0 6570.0 6174.0 5832.0 5544.0 5328.0 5112.0
 4914.0 4716.0 4518.0 4320.0 4176.0 4032.0 3870.0 3672.0 3438.0 3168.0
 2808.0 2430.0 2142.0 1764.0
     .0     .0     .0     .021366.020106.018990.017964.017028.016200.0
15408.014706.014004.013356.012780.012222.011664.011196.010602.010152.0
 9648.0 9126.0 8604.0 7992.0 7416.0 6858.0 6336.0 5904.0 5616.0 5364.0
 5130.0 4932.0 4770.0 4572.0 4446.0 4284.0 4104.0 3942.0 3780.0 3600.0
 3384.0 3150.0 2862.0 2556.0
     .0     .0     .0     .0     .020880.019710.018612.017622.016740.0
15930.015138.014472.013824.013194.012636.012132.011592.011088.010638.0
10170.0 9720.0 9288.0 8802.0 8298.0 7776.0 7200.0 6588.0 6120.0 5706.0
 5400.0 5166.0 4950.0 4752.0 4590.0 4446.0 4302.0 4158.0 4032.0 3888.0
 3726.0 3582.0 3366.0 3168.0
     .0     .0     .0     .0     .0     .0     .019224.018054.017208.0
16398.015606.014922.014256.013608.013050.012510.011988.011484.011070.0
10620.010170.0 9720.0 9324.0 8910.0 8496.0 8028.0 7506.0 6930.0 6390.0
 5904.0 5544.0 5220.0 4986.0 4806.0 4626.0 4482.0 4320.0 4176.0 4014.0
 3870.0 3762.0 3600.0 3492.0
     .0     .0     .0     .0     .0     .0     .0     .018792.017784.0
```

TEMPER (Cont'd)

```
16920.016074.015300.014634.014004.013410.012816.012348.011844.011376.0
10944.010512.010152.0 9774.0 9378.0 9000.0 8586.0 8154.0 7758.0 7272.0
 6732.0 6174.0 5688.0 5310.0 5040.0 4788.0 4590.0 4428.0 4302.0 4176.0
 4086.0 3942.0 3816.0 3690.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
17406.016560.015732.015174.014364.013752.013194.012654.012204.011700.0
11268.010836.010458.010062.0 9702.0 9360.0 8982.0 8622.0 8316.0 7920.0
 7506.0 7056.0 6570.0 5994.0 5544.0 5130.0 4860.0 4644.0 4464.0 4320.0
 4176.0 4050.0 3942.0 3816.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
     .017046.016218.015444.014724.014076.013500.012978.012492.012006.0
11556.011124.010728.010368.0 9990.0 9666.0 9306.0 8964.0 8676.0 8370.0
 8010.0 7668.0 7272.0 6840.0 6318.0 5850.0 5364.0 4968.0 4698.0 4500.0
 4338.0 4194.0 4086.0 3960.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
     .0      .016704.015840.015120.014436.013806.013266.012726.012240.0
11790.011376.010980.010620.010260.0 9864.0 9522.0 9216.0 8928.0 8640.0
 8352.0 8046.0 7704.0 7380.0 7074.0 6732.0 6246.0 5652.0 5184.0 4824.0
 4536.0 4356.0 4194.0 4068.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
     .0      .0      .016326.015552.014814.014166.013536.012996.012492.0
11898.011646.011196.010800.010440.010080.0 9738.0 9450.0 9162.0 8856.0
 8604.0 8316.0 8010.0 7776.0 7488.0 7200.0 6840.0 6462.0 6012.0 5544.0
 5040.0 4680.0 4410.0 4122.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
     .0      .0      .0      .016002.015210.014490.013878.013302.012780.0
12294.011862.011430.011052.010692.010332.0 9990.0 9666.0 9360.0 9054.0
 8784.0 8514.0 8244.0 8010.0 7758.0 7524.0 7218.0 6966.0 6660.0 6318.0
 5850.0 5400.0 4878.0 4500.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
     .0      .0      .0      .0      .015642.014886.014202.013626.013068.0
12564.012078.011628.011250.010890.010512.010170.0 9864.0 9540.0 9270.0
 9000.0 8712.0 8442.0 8190.0 7956.0 7740.0 7506.0 7236.0 7002.0 6750.0
 6444.0 6120.0 5688.0 5220.0
     .0      .0      .0      .0      .0      .0      .0      .0      .0      .0
     .0      .0      .0      .0      .0      .015336.014598.013932.013338.0
```

H (Cont'd)

```
  .0    .0122.8112.1102.4 93.1 84.5 76.5 69.8 63.1 56.7 51.5 46.4 41.5
 37.3 33.1 29.9 26.3 22.7 20.5 17.5   .0   .0   .0   .0   .0   .0   .0
  .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
  .0   .0
  .0    .0146.2134.8123.2112.6102.4 93.3 85.0 77.5 70.1 63.6 57.9 52.2
 47.1 42.1 38.0 34.0 30.3 27.1 23.4 20.1 17.4 15.3 12.8   .0   .0   .0
  .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
  .0   .0
  .0    .0174.6160.0146.2134.0122.8112.1102.7 93.7 85.4 78.0 71.0 64.5
 58.6 53.3 47.6 43.2 38.6 34.6 31.0 27.2 24.0 21.1 18.0 15.4 12.5   .0
  .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
  .0   .0
  .0223.8205.2188.5172.5158.5145.4133.2122.2111.1102.5 93.9 85.7 78.2
 71.5 65.7 59.3 53.9 48.5 43.9 39.5 35.2 31.6 28.2 24.5 21.5 18.0 15.2
 13.2   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
  .0   .0
  .0260.2238.3220.1201.2185.7171.0156.6144.0132.0121.0111.2102.2 93.5
 86.1 78.8 72.2 65.9 59.8 54.5 49.3 44.6 40.2 36.0 32.1 28.6 24.9 21.6
 18.9 16.5 12.8   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
  .0   .0
  .0298.6275.6253.6233.8215.4197.8182.3167.6154.1141.7130.6120.5110.5
101.6 93.2 86.0 78.9 72.0 66.1 60.2 55.0 49.8 45.2 40.8 36.7 32.8 29.0
 25.6 22.7 19.9 17.1 14.5   .0   .0   .0   .0   .0   .0   .0   .0   .0
  .0   .0
365.6338.8314.2289.6265.3247.1228.4210.6194.6178.8164.6151.6140.3129.4
118.6109.5101.0 93.0 85.4 78.9 72.4 66.5 60.7 55.2 50.3 45.6 41.3 37.1
 33.5 29.8 26.6 23.1 20.3 17.1 14.3   .0   .0   .0   .0   .0   .0   .0
  .0   .0
411.1382.0354.1327.7304.0281.0260.6240.7223.1206.8190.1175.2161.9149.5
137.7127.1117.5108.4100.0 92.5 85.4 78.8 72.3 66.3 60.7 55.5 50.7 46.2
 41.8 37.7 34.0 30.2 27.0 23.4 20.4 17.3 15.0   .0   .0   .0   .0   .0
  .0   .0
  .0426.7395.6368.5341.0316.1294.0272.5252.7234.5217.6201.2185.9171.8
159.1147.3135.5125.4116.0107.2 99.2 91.6 84.6 78.0 71.9 66.5 61.0 56.0
 51.2 46.5 42.4 38.3 34.1 30.8 27.3 24.0 21.1 17.9 14.7   .0   .0   .0
  .0   .0
```

TEMPER (Cont'd)

```
12960.012330.011898.011484.011052.010692.010314.010026.0 9720.0 9432.0
 9162.0 8892.0 8640.0 8424.0 8154.0 7938.0 7704.0 7470.0 7236.0 7038.0
 6804.0 6534.0 6282.0 5994.0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .014274.013644.0
13104.012564.012078.011664.011250.010872.010512.010170.0 9864.0 9576.0
 9324.0 9036.0 8784.0 8550.0 8316.0 8082.0 7848.0 7650.0 7416.0 7218.0
 7020.0 6822.0 6606.0 6354.0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .014040.0
13374.012816.012312.011862.011412.011016.010692.010350.010026.0 9738.0
 9450.0 9198.0 8946.0 8676.0 8442.0 8226.0 7992.0 7776.0 7614.0 7380.0
 7200.0 7038.0 6840.0 6624.0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
13752.013140.012564.012078.011646.011196.010818.010494.010170.0 9864.0
 9576.0 9306.0 9036.0 8784.0 8568.0 8352.0 8136.0 7902.0 7740.0 7488.0
 7344.0 7146.0 6948.0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .013482.012924.012384.011880.011412.011034.010674.010350.0 9990.0
 9720.0 9468.0 9198.0 8964.0 8694.0 8460.0 8226.0 8010.0 7830.0 7614.0
 7434.0 7254.0 7056.0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .013266.012636.012078.011610.011196.010818.010476.010152.0
 9828.0 9558.0 9270.0 9018.0 8820.0 8568.0 8334.0 8118.0 7938.0 7722.0
 7542.0 7362.0 7182.0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .012420.011916.011430.011016.010674.010332.0
10008.0 9684.0 9396.0 9144.0 8910.0 8658.0 8442.0 8244.0 8046.0 7830.0
 7650.0 7470.0 7290.0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .012222.011664.011232.010836.010476.0
```

TEMPER (Cont'd)

```
10134.0 9846.0 9540.0 9270.0 9000.0 8766.0 8532.0 8334.0 8118.0 7920.0
 7758.0 7578.0 7398.0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0    .011448.011016.010638.0
10278.0 9936.0 9648.0 9396.0 9126.0 8856.0 8622.0 8406.0 8190.0 7992.0
 7830.0 7632.0 7452.0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0     .0     .0     .0     .0
     .0     .0     .0     .0     .0     .0    .011790.011304.010836.0
10440.010080.0 9792.0 9504.0 9216.0 8964.0 8694.0 8478.0 8280.0 8064.0
 7884.0 7704.0 7506.0     .0
```

H

```
   .0   .0   .0   .0 32.1 30.5 27.0 23.6 20.5 17.8   .0   .0   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0
   .0   .0   .0   .0 43.9 38.9 34.9 31.0 27.4 24.1 21.0 17.6   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0
   .0   .0   .0   .0 54.6 49.1 44.2 39.3 35.5 31.5 28.0 24.5 21.1 18.6
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0
   .0   .0   .0 75.7 67.9 61.4 55.3 49.6 45.0 40.3 36.0 31.9 28.0 25.0
 22.1 18.5 17.1   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0
   .0   .0   .0 92.2 83.8 76.2 68.8 62.0 56.5 50.7 45.4 41.0 36.6 32.5
 29.1 25.5 23.0 19.6 17.4   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0   .0
   .0   .0
```

H (Cont'd)

```
   .0    .0439.3410.0380.8353.2328.7305.3284.4264.6246.0228.1212.0196.5
182.1168.5156.2144.7133.6123.5114.4106.0 97.8 90.8 84.1 78.0 72.1 66.5
 61.2 56.1 51.6 47.0 42.9 38.7 35.0 31.5 28.0 24.5 21.2 17.9 15.2 12.7
   .0    .0
   .0    .0    .0453.0422.8392.2365.9339.8317.4295.4275.8256.4238.7221.3
206.6191.7178.0165.4153.0142.1131.6122.1112.9104.8 97.3 90.3 83.6 77.4
 72.0 66.4 61.3 56.3 51.6 47.2 43.1 39.4 35.7 32.0 28.4 24.9 21.8 18.4
 16.2 13.1
   .0    .0    .0    .0464.1432.7404.2376.2350.8327.7306.0286.1267.0248.6
231.6216.2201.1188.8174.0162.2150.2139.6129.5119.9111.3103.5 96.0 89.1
 83.0 77.1 71.4 66.0 61.0 56.2 51.9 47.8 43.6 39.8 36.0 32.5 29.0 25.6
 22.4 19.4
   .0    .0    .0    .0    .0474.6443.9413.7386.0361.5338.3315.8295.7276.3
258.1241.5225.4210.4196.0183.3170.5158.5147.5137.0127.1118.2109.6101.6
 94.9 88.3 82.0 76.5 71.0 65.7 61.1 56.6 52.2 48.0 44.0 40.2 36.4 33.0
 29.3 26.1
   .0    .0    .0    .0    .0    .0    .0451.7420.1395.3370.8347.3325.2305.0
285.3268.0250.5234.4218.8205.3191.6178.7166.4155.2144.5134.6124.9116.0
108.1100.7 93.8 87.5 81.5 75.7 70.6 65.7 61.0 56.4 52.4 48.0 44.1 40.5
 36.7 33.3
   .0    .0    .0    .0    .0    .0    .0    .0460.2430.6404.4379.1356.0334.2
313.5294.5276.0259.1243.0228.0213.5199.7186.8174.4163.0152.6141.8131.9
123.2114.6106.6 99.6 92.7 86.3 80.8 75.2 70.1 65.2 60.8 56.5 52.4 48.3
 44.4 40.7
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0438.6412.7386.9364.1
342.3322.2302.7284.9267.9251.5236.4221.9208.1195.0182.5171.5159.8149.2
139.5130.0121.0113.0105.3 98.0 91.6 85.4 79.8 74.5 69.8 65.1 60.5 56.5
 52.3 48.5
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0447.0419.8395.0
371.7350.0329.5310.5292.6275.3260.0244.1229.5215.9202.5190.6178.1167.0
156.9146.7136.7127.6119.0111.1103.5 96.8 90.5 84.5 79.1 74.1 69.3 64.9
 60.5 56.4
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0453.8426.6
402.4379.4357.6337.6318.0300.0283.1267.4251.2237.0222.9210.0197.3185.4
174.5163.9153.5143.7134.2125.5117.0109.8102.5 95.3 89.4 83.7 78.5 73.5
 68.7 64.3
```

H (Cont'd)

```
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0   .0459.1
433.5409.4386.0364.7344.2325.0307.1290.8274.0258.8244.0230.1216.6204.5
192.8181.6170.8160.4150.3141.0131.6123.6115.4107.6100.6 94.3 88.1 82.7
 77.5 72.7
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
465.8439.8415.0392.4371.0351.0331.8314.8296.8280.6265.3250.4236.9224.0
211.6200.1188.7177.6166.8157.3147.3138.5129.4121.0113.3106.2 99.4 93.2
 87.0 81.6
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0471.0444.6420.3398.2377.2357.2338.6320.5303.7287.5271.6257.4243.9
230.8218.8206.7194.8183.7173.6163.5154.1144.5135.6127.1119.4111.7104.6
 97.8 91.7
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0475.7449.8426.3403.9383.0363.5344.5327.0309.9293.1278.1264.2
250.5237.8224.9212.9201.0190.4180.0170.0160.3150.9141.5133.3125.2117.2
110.0103.0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0455.0431.5409.7388.4368.6350.3332.3315.4299.4284.5
270.7257.2243.9231.4218.8207.6197.1186.2176.1166.5156.9148.0139.3130.8
123.0115.3
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0459.8436.0414.0393.4374.2355.2337.5321.3305.5
291.0277.0262.7249.9237.1225.2214.3202.7192.3182.1174.3162.7153.7145.1
136.6128.5
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0463.6440.8418.9398.1378.7360.1343.1326.7
311.2297.0282.0268.8255.4243.0231.5219.4208.5196.1188.0175.2168.6159.4
150.7    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0    .0468.1444.8423.3402.7383.0365.4348.0
332.0316.7301.8288.0273.9261.1249.1236.5225.1214.3203.8193.1183.6174.3
164.9    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0    .0    .0471.2449.0427.5406.7388.0369.8
```

H (Cont'd)

```
353.2337.0321.8307.2292.5279.0266.8253.9242.0230.6219.8208.3198.9189.1
179.2    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0475.0452.6431.0411.3392.0
374.9357.8341.7326.7311.4297.5284.6271.4259.0247.3236.0224.5214.4204.3
193.7    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0455.7434.6414.6
396.5379.0362.0346.2330.5316.3302.8289.0276.3264.4252.3240.5230.1219.4
208.6    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0458.7437.7
418.3400.3382.6366.2350.1335.2321.4307.0293.5281.2268.7256.7246.0234.9
223.8    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0
   .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0    .0461.2
441.2422.2403.8386.4370.0354.4340.1325.2311.2298.3285.5273.2261.9250.7
239.4    .0
```

Z

```
.00 .00 .00 .001.001.001.001.001.001.00 .00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .001.001.001.001.001.001.001.001.00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .001.001.001.001.001.001.001.001.001.001.00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .001.001.001.001.001.001.001.001.001.001.001.001.001.001.00 .00
.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .00 .00 .00 .00 .00 .00
.00 .00 .001.031.021.021.011.011.011.011.001.001.001.001.001.001.001.00
```

Z (Cont'd)

```
1.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .001.071.061.051.041.031.031.021.021.011.011.011.001.001.001.001.00
1.001.001.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .001.101.091.081.081.071.051.051.041.031.021.021.011.001.001.001.00
1.001.001.001.001.001.001.00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .001.141.131.121.111.101.091.081.071.061.051.041.031.021.021.011.01
1.001.001.001.001.001.001.001.001.00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
 .001.201.191.181.171.151.141.131.121.111.101.091.071.061.051.041.031.02
1.011.011.011.001.001.001.001.001.001.001.00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
 .001.251.241.221.211.201.181.171.161.151.141.131.111.101.091.071.061.05
1.041.031.021.011.011.001.001.001.001.001.001.001.00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
 .001.301.291.281.261.241.231.221.201.191.181.161.151.141.121.111.101.08
1.071.061.051.041.031.021.011.011.001.001.001.001.001.001.00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
1.391.371.351.331.321.291.281.261.241.231.211.201.191.181.161.151.141.12
1.111.101.081.071.061.051.031.021.021.011.001.001.001.001.001.001.00 .00
 .00 .00 .00 .00 .00 .00 .00 .00
1.461.441.421.391.371.351.331.311.291.271.261.241.221.211.201.181.171.16
1.151.141.121.111.091.081.061.051.041.031.021.011.011.001.001.001.001.00
1.00 .00 .00 .00 .00 .00 .00 .00
 .001.511.481.461.431.411.381.361.341.321.301.281.271.251.231.221.211.20
1.191.171.161.151.131.121.101.091.071.061.051.041.031.021.011.001.001.00
1.001.001.00 .00 .00 .00 .00 .00
 .00 .001.551.521.501.471.451.421.401.371.351.331.311.291.271.251.241.23
1.221.201.191.181.171.151.141.121.111.101.081.071.061.041.031.021.011.01
1.001.001.001.001.001.00 .00 .00
 .00 .00 .001.591.571.541.521.481.451.431.401.381.351.331.321.291.281.26
1.241.231.221.211.201.191.181.161.151.131.121.101.091.071.061.051.041.03
1.021.011.001.001.001.001.001.00
```

Z (Cont'd)

```
 .00 .00 .00 .001.641.611.581.541.521.491.461.431.411.381.361.341.321.30
1.281.261.251.241.221.211.201.191.181.171.151.141.121.111.101.081.071.06
1.041.031.021.011.011.001.001.00
 .00 .00 .00 .00 .001.691.641.611.581.551.521.491.461.431.411.391.361.34
1.321.301.281.271.251.241.231.221.211.201.191.171.161.151.131.111.101.09
1.071.061.051.041.031.021.011.00
 .00 .00 .00 .00 .00 .00 .001.681.641.611.581.551.521.491.461.441.411.39
1.361.341.321.301.281.271.251.241.231.221.211.201.191.181.161.151.131.12
1.111.091.081.071.051.041.031.02
 .00 .00 .00 .00 .00 .00 .00 .001.711.671.641.611.571.541.521.491.461.43
1.411.391.361.341.321.301.291.271.251.241.231.221.211.211.201.181.171.15
1.141.121.111.101.081.071.061.05
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.701.671.631.601.571.541.511.48
1.461.431.411.381.361.341.321.311.291.271.261.241.231.231.221.211.201.18
1.171.161.141.131.111.101.091.08
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.731.691.661.631.601.571.54
1.511.481.451.431.411.391.371.351.321.311.291.271.261.251.241.231.221.21
1.201.191.181.161.151.141.121.11
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.751.721.681.651.621.59
1.561.531.501.481.451.431.411.381.361.331.311.301.291.271.261.251.241.23
1.231.221.211.191.181.161.151.14
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.771.741.711.681.64
1.611.581.551.531.501.471.451.421.401.381.361.341.321.301.291.271.261.25
1.241.241.231.221.211.201.181.17
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.801.771.731.70
1.671.631.601.571.541.521.491.471.441.421.401.381.361.341.321.301.291.27
1.261.251.241.241.231.221.211.20
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.831.781.75
1.721.681.651.621.591.571.541.511.491.461.441.421.401.381.361.341.321.30
1.281.271.251.251.241.241.231.22
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .001.851.81
1.771.741.711.681.641.611.581.561.531.501.481.461.441.411.391.381.361.34
1.321.301.281.271.261.251.241.23
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
1.831.791.761.731.691.661.631.601.571.551.521.501.471.451.431.411.391.37
```

Z (Cont'd)

```
1.351.331.321.301.281.271.261.25
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .001.851.811.781.741.711.681.651.621.591.571.541.521.491.471.451.431.41
1.391.371.351.331.311.301.281.27
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .001.861.831.791.761.731.701.671.641.611.581.561.531.511.491.461.44
1.421.401.381.361.341.331.31 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .001.881.851.811.781.741.721.691.661.631.601.581.551.531.501.48
1.461.441.421.401.381.361.34 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .001.901.861.831.791.761.721.691.671.641.621.591.561.541.52
1.501.481.461.431.411.391.37 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .001.911.871.841.811.781.751.721.691.661.631.601.581.56
1.531.511.491.471.451.431.41 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .001.891.851.821.791.761.731.701.671.641.621.59
1.571.551.521.501.481.451.43 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .001.901.871.841.811.771.741.721.691.661.63
1.611.591.561.541.521.491.47 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00 .00
 .00 .00 .00 .00 .00 .00 .00 .00 .001.911.881.851.821.791.761.731.701.67
1.641.621.601.571.551.531.51 .00
```

REFERENCES

1. W. D. Hayes and R. F. Probstein, Hypersonic Flow Theory, Academic, 1959, p. 230.

2. R. F. Probstein, "Shock Wave and Flow Field Development in Hypersonic Reentry," Am. Rocket Soc. J., Vol. 31, No. 2, February 1961, pp. 185-194.

3. Normal and Oblique Shock Characteristics at Hypersonic Speeds, Report No. LB-25599, Douglas Aircraft Co., Inc., Santa Monica, California, 31 December 1957.

4. S. Feldman, Hypersonic Gas Dynamic Charts for Equilibrium Air, Research Report No. 40, Avco-Everett Research Laboratory, Everett, Mass., January 1957.

5. G. T. Chapman, Theoretical Laminar Convective Heat Transfer and Boundary-Layer Characteristics on Cones at Speeds to 24 km/sec, NASA TN D-2463, National Aeronautics and Space Administration, August 1964.

6. M. D. Van Dyke, "The Supersonic Blunt-Body Problem--Review and Extension," J. Aerospace Sciences, Vol. 25, No. 8, August 1958, pp. 485-496.

7. G. G. Chernyi, Introduction to Hypersonic Flow, Academic, 1961, p. 201.

8. G. N. Patterson, "A Synthetic View of the Mechanics of Rarefield Gases," AIAA J., Vol. 3, No. 4, April 1965, pp. 577-590.

9. H. Y. Wachman, "The Thermal Accommodation Coefficient: A Critical Survey," Am. Rocket Soc. J., Vol. 32, No. 1, January 1962, pp. 2-12.

10. J. A. Fay and F. R. Riddell, Theory of Stagnation Point Heat Transfer in Dissociated Air, Research Report No. 1, Avco-Everett Research Laboratory, Everett, Mass., April 1957.

11. N. H. Kemp, P. H. Rose, and R. W. Detra, Laminar Heat Transfer Around Blunt Bodies in Dissociated Air, Research Report No. 15, Avco-Everett Research Laboratory, Everett, Mass., May 1958.

12. P. Miles and G. Waldman, Laminar Boundary Layer Skin Friction, Heat Transfer, and Displacement Thickness Correlations for Sharp Cones (Task 3.1--Flow Field Analyses--Rest Program), Report No. RAD-TM-62-90, Avco Corporation, RAD, Wilmington, Mass., November 1962.

13. Semi-Annual Report on the Reentry Problem, Period Covering 1 January 1957 - 30 June 1957 (U), Reference No. 02551-39, Avco Corporation, RAD, Wilmington, Mass. (SECRET).

14. M. J. Brunner et al., Flow Field Prediction and Analysis Project Fire, Report No. 64SD727, General Electric Co., Philadelphia, Pa., May 1964.

15. E. R. Van Driest, "The Problem of Aerodynamic Heating," Aeron. Eng. Rev., Vol. 15, No. 10, October 1956.

16. Eighth Annual Report of the Ballistic Missile Radiation Analysis Center (U), (17 October 1966 through 31 October 1967), Report No. 8416-21-F, Vol. II, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, Michigan, May 1968 (SECRET).

17. R. W. Detra and H. Hidalgo, Generalized Heat Transfer Formulae and Graphs, Research Report No. 72, Avco-Everett Research Laboratory, Everett, Mass., March 1960.

18. L. W. Warzecha, Effect of Trajectory Variation on Reentry Phenomena WS-107A Nose Cone (U), Report No. DF-56SD25, General Electric Co., Philadelphia, Pa., March 1956 (SECRET).

19. Robert Siegel and John R. Howell, Thermal Radiation Heat Transfer, Vol. I: The Blackbody Electromagnetic Theory, and Material Properties, NASA SP-164, Lewis Research Center, 1968.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) General Research Corporation, Washington Operations 1501 Wilson Boulevard Arlington, Virginia 22209	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

FINAL REPORT FOR THE OPTICAL SIGNATURES PROGRAM

Volume VI: EXOATMOSPHERIC TARGET SIGNATURES CODE (EXOSIG) USER'S MANUAL

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5. AUTHOR(S) (First name, middle initial, last name)

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1971	viii + 128	19

8a. CONTRACT OR GRANT NO. DAHC60-70-C-0078 b. PROJECT NO. ARPA Order 1292, Amendment 3 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) CR-2-184 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

This document may be further distributed by the holder only with specific prior approval of the U.S. Army Advanced Ballistic Missile Defense Agency, Huntsville, Alabama.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U.S. Army Advanced Ballistic Missile Defense Agency, Huntsville, Alabama 35807

13. ABSTRACT

(U) The exoatmospheric target signature code (EXOSIG), a segment of the Optical Signatures Code (OSC), is designed to calculate the optical signatures of targets (reentry vehicles, decoys, etc.) during exoatmospheric flight. EXOSIG is divided into nine distinct sections, two of which supply information to the remaining sections and not to the user of the code. These two routines (TARG and EARTH) are, therefore, presented as appendixes rather than in the main body of this volume. The remainder of the exoatmospheric code is comprised of seven primary sections, each of which is available to the user depending upon which types of targets and calculations he desires. Any number of calls may be made to any number of routines. An end-of-file test will terminate the job. The physics utilized in the development of each section's code and the input/output information necessary to or resulting from each of the calculations is different for each section and is presented. The choice of which routine (available to the user) is required by him is based upon the target configuration, its surface material properties, and whether the user desires the target's optical signature or the polarization content of its optical signature. (U)

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Optical materials						
Infrared radiation						
Exoatmospheric radiation						
Ballistic missiles						
Reentry vehicles						
Computer simulation						